



THE ROLE OF PHYSICS IN AERONAUTICAL DEVELOPMENT

**Hugh L. Dryden, Director
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**Presented before the Section on Physics,
American Association for the Advancement of Science,
at the Conference on Applied Physics,
Room D, Municipal Auditorium, Philadelphia.**

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Goals of Aeronautical Development

The present aim of aeronautical development is to attain superiority in performance and military effectiveness of our aircraft and missiles with the hope of maintaining peace by deterring aggression. For the aircraft designer the principal technical goal is the design and construction of a vehicle which will move more rapidly from one place to another over the surface of the earth, climb faster to higher altitudes, and carry larger loads to greater distances. All this must be done as economically as possible as measured by initial investment of materials and labor and by operating cost. Other technical goals relate to the ability to operate in bad weather and darkness, to the ability to communicate with ground stations and other aircraft, and to the specifically military functions of locating and destroying military targets, and of self-defense. However, the present discussion will be limited to the performance of the airplane or missile as a vehicle. Development is taken to include the associated applied research, and the examples

of the application of physics to aeronautical development are taken largely from the work of the National Advisory Committee for Aeronautics, which is an independent civilian agency of the government with responsibility for basic and applied research in aeronautics, or, in the language of the legislation establishing the agency, "for the scientific study of the problems of flight with a view to their practical solution".

If we are to study the role of physics in aeronautical development, we must agree on the content to be ascribed to physics, a task which many eminent physicists have found very difficult. For our purposes it is sufficient to define physics as the activities of persons who call themselves physicists, and to supplement this definition by the 758 subject index headings grouped under 32 principal headings under the title Physics in Physics Abstracts. A cursory survey shows well over 100 topics in this list which are of great importance to aeronautical development. It is obvious that this brief paper can only touch on a few examples.

Aeronautical engineering has matured on the basis of theoretical and experimental research with little of the tradition of empirical practical knowledge characteristic of other engineering fields. This reliance on scientific methods is in part dependent on the accuracy of design required to make an airplane fly safely with a useful payload and in part on the comparatively late development of aeronautics at a time when scientific research methods were well developed. From its very beginning aeronautics has applied basic physical knowledge to improvements in engineering design and has sought to convert

the results of research in physics into useful aeronautical devices. In the past few years the accelerated pace of aeronautical development following the introduction of rocket and jet engines and the accumulation of knowledge of supersonic aerodynamics has reversed the direction of influence. Now the aeronautical engineer breaks down his new and difficult engineering problems into their component problems in physics, and brings pressure on physicists to study these component problems by physical methods. This extension of the engineering development team to physicists has brought added opportunities for the employment of physicists. More important to physics, however, is the large number of new challenging problems in both applied and pure physics brought to light by close contact with a rapidly growing engineering field.

Aerodynamics Gives Rise to Physics Problems

The Goal of Higher Speed

Let us look at some of the problems in physics associated with increasing the speed of aircraft and missiles. The speed at any given altitude is dependent on the drag force exerted by the air on the moving body and on the power available. As is well known, research airplanes have been flown by human pilots well above the speed of sound and missiles such as the German V-2 travel at speeds of several times the speed of sound. Speeds of both aircraft and missiles are measured in terms of the ratio of speed to

the speed of sound, this ratio being called the Mach number after the famous physicist, Ernst Mach. As the speed approaches the speed of sound, shock waves develop in the flow and are often accompanied by flow separation. When this occurs, the air flows past the airplane with violent fluctuations, shaking or buffeting the wing, and if the violently disturbed wake strikes the tail the buffeting loads may be sufficient to produce structural damage. The flow separation is the result of an interaction between the shock wave and the thin layer of air near the surface in which viscous forces are appreciable, being in fact sufficient to bring the relative air speed to zero at the surface. The study of shock waves, of shock-wave boundary-layer interactions, and of the reflection, refraction, and mutual interference of shock waves are problems for the physicist and are best studied by physical methods.

In low speed flows, data on the flow field can be obtained by static pressure probes, but at transonic and supersonic speeds it is difficult to measure pressures accurately with probes. The very presence of the probe may change the flow considerably. Even pressure orifices in the walls do not give reliable measurements in the presence of shock waves and other large pressure gradients. The experimental physicist offers a solution to this problem by various optical devices including the interferometer.

Ladenburg, Bleakney, and other physicists have used this instrument to add greatly to our knowledge of shock-wave phenomena. Aeronautical research scientists too have adopted the interferometer for studies of supersonic flow fields about wing sections and aircraft models. Fig. 1 shows an instrument

used by Wood and Gooderum at the NACA Langley Laboratory (NACA Report 963) and Fig. 2 is an interferogram obtained with it of the flow about a 12-percent-thick biconvex circular-arc airfoil at a Mach number of 0.9 with turbulent boundary layer.

Most of the theoretical analyses of compressible flow have been made on the assumption of isentropic flow. As the speed is increased and shock waves appear in the flow, this assumption becomes unsatisfactory. For shock waves of moderate strength the equations of Rankine and Hugoniot may be applied, but for strong shock waves additional effects appear because of the excitation of vibrational degrees of freedom of the diatomic molecules and because of departures from the ideal gas law associated with finite molecular size and with intermolecular forces.

When the Mach number exceeds 5, the speed is said to be hypersonic. At hypersonic Mach numbers of 10 or more, the estimated rise in temperature at the stagnation point is sufficient to cause both molecular dissociation and atomic ionization of the air. The effect of dissociation and ionization is to lower the stagnation temperature below the adiabatic value because of the internal absorption of energy necessary for increased rotational and vibrational energy and dissociation and for electronic excitation and atomic ionization. At the NACA Langley Laboratory exploratory work has been done in this field by firing projectiles through gases in which the velocity of sound is much lower than in air at normal temperatures and can be further reduced by cooling to very low temperatures (NACA Technical Note 2120).

With moderate projectile speeds a Mach number of 10 is readily obtainable. The equipment is shown schematically in Fig. 3. In a recent experiment by Sabol a 1/8-inch diameter conical projectile was fired at 6000 ft./sec., using a 30-caliber sabot, through Xenon gas at 74° F. and atmospheric pressure, and giving a Mach number of 11. As shown in Fig. 4 the gas was made luminous in a region near the nose. The calculated temperature behind the shock wave was 2846° K. and it was estimated that 0.1 percent of the Xenon atoms were ionized.

In high-velocity flow around bodies where the temperature changes rapidly, there may be a failure of the internal energies of the gas molecules to adjust sufficiently rapidly to be in equilibrium with the temperature corresponding to the translational motion of the molecules. This effect, commonly called heat-capacity lag, can be computed if the number of molecular collisions required to establish equilibrium is known for the gas or gas mixture. Physicists usually measure this lag by sound-dispersion methods using acoustic interferometry, the changes of sound velocity with frequency being attributed to heat-capacity lag. At the NACA Langley Laboratory a gas-flow method has been used (NACA ARR 4A22), in which the loss of total pressure is measured for a flow accelerated from rest to high subsonic speeds and then suddenly brought to rest at the nose of a small impact tube.

It is well known that meteors traveling through the air at high supersonic speeds get so hot from friction with the air that their surface melts. At lower supersonic speeds the heating is by no means negligible, and must

be considered even at subsonic speeds for piloted aircraft. Fig. 5 shows a small heat-flow meter used for flight measurements at the NACA Ames Laboratory and Fig. 6 their installation on the plastic canopy of an F-80 airplane. It appears that limits set by aerodynamic heating and the adequacy of measures to control its effects may constitute the next most important barrier to still further speed increases. This problem is one which must be attacked by the methods of the physicist.

These are a few of the aerodynamic problems on the advancing frontier of speed which give rise to problems in physics. There are many others of more immediate concern to designers of current transonic airplanes but these have been avoided in this paper for security reasons. They are being attacked both by theoretical and experimental methods. The most useful experimental tool is the wind tunnel, which has itself undergone rapid development with great assistance from physics and physicists. Electrical wire strain gages have revolutionized wind tunnel balances; and shadow, schlieren, and interferometric methods make many features of the flow field visible.

Wind Tunnel Development Needs Research in Physics - the Condensation Problem

As the speed frontier advances, it is necessary to develop wind tunnels capable of studying the problems of flight at ever increasing speed. A supersonic wind tunnel of cross-section 8- by 6-feet and 87,000 horsepower is in regular operation at speeds up to twice the speed of sound. Exploratory

work is in progress in small equipment at much higher speeds, and this work has revealed difficult technical problems. The high speed in the test section of a supersonic wind tunnel is obtained by expanding air from a pressure of one atmosphere or a few atmospheres to a very low pressure, and the expansion is accompanied by a considerable reduction in temperature. Even in wind tunnels operating at transonic and low supersonic speeds, the lower temperature may lead to the condensation of the water vapor present in the air stream with resulting modification of the forces experienced by models being tested. To avoid this condensation, supersonic wind tunnels are equipped with air dryers to reduce greatly the amount of water present.

When the Mach number becomes of the order of 7 to 10, the temperature is sufficiently low to lead to condensation of the oxygen and nitrogen in the air. One method of alleviating the difficulty is to preheat the tunnel supply air above atmospheric temperatures. In order to design intelligently a hypersonic wind tunnel, it is necessary to know much more than we do now about condensation phenomena. According to some theories, condensation might not occur if the traverse time of air through the low temperature region were sufficiently short. All theories require the presence of condensation nuclei. What are the nuclei responsible for condensation in hypersonic wind tunnels? Does condensation occur at the saturation temperature or is some degree of supersaturation possible? These are the questions which physicists are asked to answer.

Some recent progress has been made in this field by Williams and

McClellan of the NACA Langley Laboratory working in an 11-inch hypersonic wind tunnel. The presence of condensation was first inferred from pressure surveys such as those shown in Fig. 7. Later confirmation was obtained by the simple light-scattering technique illustrated in Fig. 8 with typical results illustrated in Fig. 9. The first experiments indicated a large degree of supersaturation. The equipment was then refined to make possible measurements of the amount of light scattered at given angles and the amount of light absorbed by a volume element at various points along the axis of the stream. From these measurements the particle size and the number of particles per unit volume were computed as a function of distance along the stream axis. The details of the method are described in NACA Technical Note 2441 by Durbin. The rate of particle growth and the resulting local pressure could then be calculated. The calculated pressure agreed with the measured pressure and the air stream remained essentially at the saturation temperature after the condensation particles became large enough to be detected by the light-scattering equipment. A more sensitive system moved the detection point closer to the computed saturation point in the nozzle. Since the amount of light is principally a function of particle radius, the number of particles per unit volume could be assumed to be constant, and the last points plotted with the earlier data to give the particle size as function of distance along the nozzle axis. This curve extrapolated to zero diameter at the saturation point in the nozzle, verifying the conclusion that in the experiments air condensed with practically no supersaturation.

The next problem was to determine the source of the condensation nuclei which correspond to the dust nuclei responsible for the formation of atmospheric fog. Since there were some 10^{10} particles per cubic centimeter, the possible existence of stable foreign particles was dismissed and the effect of the presence of water vapor was studied. The water content was varied from about 1 part in a million to 1 part in 2,000. Measurements of particle radius and number of particles per unit volume indicated no effect until the water vapor content reached 1 part in 2,500.

Attention is now directed to carbon dioxide as the probable source of the condensation nuclei, since measurements showed this gas to be present at a volume concentration of about 1 part in 10,000 and to remain fairly constant throughout long periods of time. Results on effects of varying the carbon dioxide content are not yet available.

Research in aeronautics owes a great debt to physics not only for the development of many tools for its own research which find application in aeronautical research, but also for rich resources of physical principles from which ingenious men may draw to devise methods of measuring almost any physical quantity under the most varied circumstances. Hypersonic wind tunnels present many instrumentation problems in which physics has come to the rescue. For Mach numbers in excess of 5 the conventional type of pressure-measuring equipment is no longer adequate. Recourse has therefore been made to McLeod gages. In the NACA Ames 10- by 14-inch hypersonic wind tunnel (Fig. 10) a battery of 40 of these gages has been mounted on a

manometer board, as shown in Fig. 11, to facilitate the measurement of 40 pressures at the same time by the adjustment of one common sump. In this way the pressure distributions may be photographed in much the same manner as they are on a conventional U-tube manometer board. The low pressures are also accompanied by low densities, requiring the use of long wavelength X-ray apparatus rather than the interferometer to determine densities in flow fields about models.

The Goal of Higher Altitude

Operation at ever higher altitudes is a second aim of the aircraft designer, and efforts to increase operating altitude also bring many problems in physics. Missiles have already penetrated to extreme altitudes. If the altitude becomes sufficiently high, air can no longer be considered as a continuous medium. The mean free path of the molecules becomes comparable with characteristic lengths of the flow, for example boundary layer thickness or shock wave thickness. Slip flow will occur at the boundary as the pressure is reduced and ultimately the molecular interaction with the boundary must be considered. At very low pressures the gas may be considered as a stream of free molecules, to which the classical mathematical theory developed by Maxwell, Knudsen, Smoluchowski, Boltzmann and others may be applied. Slip flows may be attacked theoretically by the methods of Chapman and Cowling, Schamberg and others, which apply to slightly rarefied gases.

At the NACA Ames Laboratory, the University of California at Berkeley, and at other laboratories physicists are engaged in the experimental exploration of low density flows. The Ames low-density wind tunnel uses a type of oil-diffusion pump developed in connection with the atomic bomb program. The pressure-measuring instrumentation consists of several types of gages, McLeod, Pirani, and ion gages, which were developed and first used in physics laboratories. The flow visualization method used is a direct result of the work of Dr. Joseph Kaplan of the University of California at Los Angeles on the afterglow of excited nitrogen gas. The intensity of the luminescence which persists for an appreciable time after nitrogen is electrically excited to states capable of emitting light increases with increasing density. This phenomenon can be used at low density to give the same general picture of shock-wave location and density variation as is given by schlieren apparatus at higher density. Fig. 12 shows the flow about a 30° wedge at Mach number 2 and 140 microns of mercury stagnation pressure obtained by this method. The thick shock wave is typical of low-density flows. The physicist's torsion balance has been adapted to measure drag forces of the order of one milligram. The speed of flow has been measured by ionizing a small "lump" of air and electronically timing its travel between two electrodes spaced a known distance apart. One of the first investigations in this low-density wind tunnel is described in NACA Technical Note 2244 by Stalder, Goodwin, and Creager under the title "A Comparison of Theory and Experiment for High-Speed Free-Molecule Flow."

Speed-Altitude Survey of Aerodynamics

Numerous attempts have been made to classify the aerodynamic problems associated with the entire range of speed, altitude and vehicle size, and to map the boundaries between regions in which Reynolds number, Mach number, and Knudsen number are in turn the predominant controlling parameter. Such boundaries are not at all sharp and depend on the body shape. There are wide regions in which the influences of two or all three of the parameters are comparable.

When the Mach number is small (less than 0.5) and the Knudsen number is small (less than 10^{-3}), the controlling parameter determining the nature of the flow field is the Reynolds number $R = \frac{VD\rho}{\mu}$, V being the speed, D a linear dimension fixing the scale, ρ the density, and μ the viscosity of the fluid. Thus for a circular cylinder, if the Reynolds number is unity or less, the inertia forces are small compared to the viscous forces, and we have the type of flow known as "creeping" flow. As the Reynolds number is increased, the viscous effect becomes concentrated in a thin laminar boundary layer and elsewhere in the field the inertia forces predominate. When the Reynolds number reaches about 500,000, the laminar boundary layer becomes turbulent before separation and the flow field assumes a different configuration. When the Mach number is increased to supersonic values, the same phenomena occur although the limiting values of Reynolds number change somewhat because of temperature changes produced by the motion.

According to the kinetic theory of gases the viscosity μ is equal to $0.499 \rho \bar{v} \lambda$ where \bar{v} is the mean velocity of the molecules and λ is their mean free path. The mean velocity \bar{v} is related to the speed of sound a and the ratio of specific heats γ by the equation $\bar{v} = \sqrt{\frac{8}{\pi \gamma}} a$. Hence for air the Reynolds number R is equal to $1.486 M/K$ where M is the Mach number V/a and K is the Knudsen number λ/D . λ is chiefly a function of the pressure p , hence of altitude, although there is a small temperature effect. Thus

$$\lambda p/p_a = 2.32 \times 10^{-6} + 1.18 \times 10^{-8} t^0 \text{ inches}$$

where p_a is a pressure of one atmosphere. It seems probable that it may be more useful to express the Knudsen number in terms of the boundary layer thickness δ_s^* at the stagnation point. For a cylinder $\lambda/\delta_s^* = 3.82\sqrt{MK}$. Thus we may regard M and K as the basic parameters which appear only in the combination M/K at subsonic speeds and low altitudes.

A rough general survey of the whole domain can then be obtained by plotting boundary loci on a chart with M as ordinate and λ/D as abscissa as shown in Fig. 13. Logarithmic scales are most convenient since most of the boundaries are straight lines. The figure indicates Reynolds number boundaries for creeping flow, laminar and turbulent boundary layers and λ/δ^* boundaries for free molecule, slip and continuum flow. As δ^* approaches D , the λ/δ^* is modified to λ/D . The abscissa can be interpreted mainly as an altitude scale for a given value of D and the

ordinate as a speed scale. As a matter of interest, the operating lines for a 1-inch and 2-inch model in a supersonic wind tunnel with atmospheric stagnation pressure are shown. Care must obviously be taken in the interpretation of measurements in a supersonic wind tunnel in which several boundaries are crossed as the speed is varied. As previously mentioned, the boundaries are not sharp and such a chart is useful only to indicate where difficulties should be looked for. The effects of aerodynamic heating have not been included.

Aircraft Propulsion Gives Rise to Physics Problems

The attainment of high speed in aircraft and missiles is dependent not only on a detailed knowledge of aerodynamics and in particular on methods of reducing drag by such measures as sweeping back the wings and reducing their thickness, but also on the development of power plants of low weight, high thrust per unit frontal area, and low fuel consumption. Supersonic flight has come with the turbojet and rocket types of power plant. Engineering development of these power plants has brought to light many problems in whose investigation the interests, techniques, and outlook of the physicist play a prominent part. These include problems relating to the aerodynamics of compressors and turbines, to fuels and to their combustion in high speed air streams at rates far exceeding those present in other industrial devices and at very low pressures, to materials for use at temperatures up to 3500° F., to heat transfer and cooling, to friction and

high speed bearings, and to controls, sensing devices for speed, pressure and temperature, and servomechanisms.

As a typical example, development work on combustors emphasizes the importance of understanding the fundamental nature of initiation and propagation of flames. Some of the problems under study at the NACA Lewis Laboratory and to which physicists might well devote greater attention are described in the following paragraphs.

A knowledge of the minimum spark ignition energies associated with a wide range of fuel-to-air mass ratios, pressures, temperatures and other variables is essential to the successful design and operation of ramjet and turbojet engines. A program of research is now under way to

- (a) Measure the minimum spark ignition energies associated with a quiescent gaseous fuel and air mixture under varying conditions of temperature, pressure, fuel-to-air ratio, molecular fuel type and geometrical configuration of the ignition bomb.
 - (b) Measure the minimum ignition energies associated with a gaseous fuel and air mixture flowing irrotationally past the ignition source, studying the effect of the variables previously listed.
 - (c) Measure the minimum spark ignition energies associated with a fuel and air mixture in turbulent flow, with studies of the effects of the variables previously listed.
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- (d) Interpret the data in the light of existent theories, and to formulate a theory consistent with the ignition data as well as with data from allied branches of the combustion field. The exact nature of the ignition process as well as the full meaning of "ignition energy" are still a challenge to the physicist.

The maximum thrust available from a jet engine is closely related to the maximum fundamental flame speed associated with a given fuel and air system. One technique employed for measuring flame speed utilizes two photocells, each giving a narrowly collimated view of a transparent cylindrical flame tube, to turn an electronic counter on and off respectively (Gerstein, Levine and Wong in *Journal of the American Chemical Society*, vol. 73, pp. 418, 1951). This yields the time during the traverse of a known distance by the flame front. Many problems of instrumentation, interpretation of data in terms of the geometry of the apparatus and the aerodynamics and kinetics of the situation are being and remain to be attacked by the physicist.

In a liquid-fuel rocket, ignition is obtained spontaneously when two fluid jets (fuel and oxidant) contact each other. Assurance of this continuous ignition process in a rocket combustor depends upon a great multitude of physical and chemical factors whose individual roles in the ignition and combustion processes must be determined both experimentally and theoretically.

As an example of a new problem for the physicist arising in engine

development, we may take the fluctuations in the spray pattern formed by two impinging jets, described in greater detail by Heidmann and Humphrey of the NACA Lewis Laboratory in NACA Technical Note 2349. The combustion process in rocket engines has, under certain operating conditions, exhibited a state of instability, characterized by sustained oscillations in combustion chamber pressure and thrust at frequencies that vary from approximately 20 up to several thousand cycles per second. The low frequency oscillations may be due to resonance in a circuit where the propellant feed system and the rocket chamber are dynamically coupled. Instability at high frequencies appears to be associated with the injection and mixing process. It was found that when two jets of water impinged, a ruffled sheet of liquid was formed with waves perpendicular to the plane of the two jets. (See Fig. 14). The liquid sheet disintegrated intermittently, forming groups of drops, which appeared as waves propagating from the point where the two jets meet. Fig. 15 shows five successive frames from a high speed motion picture of the phenomenon. The wave length and spacing was variable in random fashion about average values but the frequency was approximately constant over short periods of time at values between 1,000 and 4,000 cycles per second for the range of test conditions. It appeared that the ruffling of the liquid sheet persisted to the point of disintegration of the sheet and determined the frequency of the wave formation. Irregularities in the jets before impingement may be as instrumental in controlling the ruffling of the liquid sheet as is the friction of the air. Here is a problem to be explored

more fully by physicists.

One aspect of jet engine fuel performance of great practical interest is its tendency to form carbon deposits in the combustor. A completely satisfactory explanation of the carbon formation mechanism in flames has yet to be given. If the fundamental molecular processes giving rise to sooty flames were fully understood, a significant step towards the improvement of jet engine performance and longevity would be possible. Fundamental studies of various types of flames are under way, with spectroscopic and photographic techniques being employed to obtain data concerning the gross physical as well as the molecular properties in the various regions of the flames. The role of additives in the suppression of carbon formation is also being considered.

The basic principles of physics are continually utilized in the study of lubrication, friction, and wear of bearings and gears. Damage to the surfaces of the bearings and gears is usually more important than the magnitude of the friction. The physical and chemical conditions at the surface are of utmost importance in determining the type of surface damage, whether smooth sliding, shearing of low-shear-strength surface films, or severe surface adhesion or even welding. Surface films of thickness of a few millionths to ten-thousandths of an inch often form naturally and are of great practical importance. X-ray and electron diffraction techniques are used to measure lattice parameters and hence chemical composition as well as to detect the presence of preferred orientation of the molecular constituents.

In the propulsion field, a great variety of physical principles are applied to special experimental techniques. Thus Bundy, Strong and Gregg of the General Electric Company (Journal of Applied Physics, vol. 22, August 1951) combined interferometry and spectroscopy to measure the velocity and pressure of gases in a rocket flame. The method was based on the Doppler shift of wave length of the sodium or lithium spectral radiation from the flame when viewed at different angles relative to the flame axis.

An interesting recent development by Warshawsky and Shepard of the NACA Lewis Laboratory is an air-cooled thermocouple (Fig. 16) which can be used to measure temperatures above the melting point of the thermocouple material. Three thermocouple junctions are employed at the middle and ends of a horizontal wire between two supports, the hot gas flow being normal to the wire. The hollow supports are cooled by an air stream to keep the wire at a temperature well below the melting point of the material, the heat from the center being conducted along the thermocouple wire to the other junctions located at the cooler supports. Increased gas temperature requires a higher cooling air-flow rate and a greater temperature difference between the central junction and the supports. Hence this temperature difference is a measure of gas temperature at a fixed Mach number and pressure.

Problems in Physics Associated with Aircraft Materials and Structures

At extremely high speeds aerodynamic heating will increase temperatures to the point where the commonly used materials lose a large percentage

of their strength. Likewise the introduction of thin wings and unusual plan forms yield more flexible structures with interactions between structural deformation and aerodynamic loads. Vibration and flutter problems become more severe. New materials must be sought and potentially available materials such as the stainless steels and titanium alloys must be thoroughly exploited and evaluated. Thermal insulation and cooling of the structure become possible methods of attack on the design problem.

In engine materials, the field of high-temperature alloys is of special significance. During the last war, American manufacturers turned out 257,000 piston engines for airplanes in a single year. If the present emergency were to worsen to the point where even 100,000 of the higher-powered jet engines had to be built annually, it would be necessary to cut down on the amounts of the strategic materials, columbium, cobalt, tungsten, chromium, and nickel used in their manufacture. This problem is under vigorous attack and physicists play an important role in alloy development and evaluation and in the study of alternate methods of dealing with the problem such as turbine blade cooling.

A few examples in this field will illustrate the role of physics. The property of greatest interest at high temperature is creep, yielding of the material at constant load. The electron diffraction technique has been applied to the study of the effect of surface films on the creep of a metal crystal. Fig. 17 shows a plot of elongation vs. time for a single crystal of zinc and corresponding electron diffraction patterns, first for the crystal

with a surface film of oxide, and then with surface film removed by acid.

Aeronautical engineers are greatly interested in progress in the physics of solids as throwing light on the mechanisms of plastic flow and creep. The aircraft, engine, or missile designer is interested in establishing the relation between stress and strain under polyaxial stress conditions as a function of previous history of loading and time. Various phenomenological approaches have been made by applied mathematicians and engineers. The physicist can contribute by investigating the plastic behavior of metals on the basis of the microscopic processes that take place within metallic grains deforming plastically. One of his goals then becomes the synthesis of a stress-strain relation on the basis of these elementary processes; ultimately the physical approach and the phenomenological approach may be expected to yield a common end product.

Batdorf and Budiansky (NACA Technical Note 1871) of the NACA Langley Laboratory proposed a slip theory derived from physical considerations. The assumption was made that plastic deformation is due wholly to slip along crystallographic planes of individual metal crystals, that slip is caused by shear stress only, that the magnitude of the slip depends upon the magnitude of the stress, and that the slip of a particular crystal is not influenced by that of neighboring crystals. The plastic deformation of the material as a whole is then considered to be given by the cumulative effect of the slip that has occurred in all of the crystals. While the experimental checks of the theory have given agreement in some cases, and have been

disappointing in others, it is felt that this type of approach is worthy of further study.

A typical modern structures problem is that of avoiding flutter, a self-induced sometimes catastrophic vibration of the structure. This field affords many illustrations of the role of classical mechanics applied under rather unusual circumstances. The necessity for including both aerodynamic and structural terms in the analysis of the rather flexible structures of aircraft and missiles leads to nonsymmetric cross-coupling terms and to such difficulties as non-self-adjoint differential equations, a field only slightly investigated. The theory of nonsteady or oscillatory airflow is based on appropriate distributions of moving acoustic sources and doublets corresponding to those appearing in classical wave propagation formulas. To obtain good measurements of the oscillating air forces or pressures on a wing at high Mach numbers requires excellent instrumentation and exacting techniques which physicists are well qualified to devise. One useful experimental technique is the use of Freon 12 as a test medium in conjunction with admixed air and variable density in a flutter wind tunnel.

Aircraft Operation Offers Challenging Physics Problems

Aircraft Icing Problems

There are many challenging problems in physics arising in the operation and use of aircraft. It is desired to fly aircraft in all kinds of

weather. We are immediately confronted with problems of the physics of clouds because clouds can cause ice formation on the aircraft, interference with radar operation, turbulence, and limitation of visibility. Studies are under way at the NACA Lewis Laboratory on the liquid-water content, droplet size, and droplet size distribution found in natural clouds, on the physical properties of supercooled water, on the measurement of water vapor, and on the physical mechanism of icing.

Two methods of measuring droplet size have recently been developed which work at temperatures above freezing. One employs a coronal discharge to put electrostatic charges on the cloud droplets which are then collected by suitable electrodes (NACA Technical Note 2458); the other is based on the principle of inertia separation in a low speed air stream. (NACA Research Memorandum E51G05). Cameras designed for use in flight have been developed by both the NACA Lewis Laboratory and the Canadian National Research Council to photograph cloud droplets in a natural suspension in the atmosphere (NACA Research Memorandum E50K01a). Droplets of diameter greater than 5 microns are recorded. The shadowgraph in Fig. 18 shows droplets 25 to 60 microns in diameter in an artificial cloud with number of particles per unit volume comparable to values for natural clouds.

The effect of droplet size and impurities on the freezing temperature of water droplets supported by a metallic surface has been investigated. (NACA Technical Notes 2142 and 2234). It has been found that on the

average the smaller droplets supercool to lower temperatures than the large droplets, especially for droplets below about 60 microns in diameter. In addition there is wide variation in the freezing temperatures of droplets of a given size because of the effect of impurities which are present in the water or come in contact with its surface. Fig. 19 shows droplets on a cooled plate at -10° F. The droplets range in size from 8 to 500 microns and those that are liquid can be distinguished by the highlights on the surface whereas the frozen ones are opaque or milky white. The largest drop froze at 0° C.

A preliminary photographic study of the freezing of droplets falling freely in a cold air stream yielded statistical results in rough agreement with those for droplets on a metallic surface. X-ray diffraction studies of the internal structure of supercooled water indicate that the internal structure becomes progressively more ice-like as the temperature is lowered.

The most frequent form of aircraft icing occurs in flight through clouds composed of supercooled liquid water droplets. Upon impact with exposed parts of the airplane the droplets freeze and adhere to the surface. The mechanism of droplet interception by an airfoil is a process of inertia separation.

Reduction of Aircraft Noise

Another operating problem of great current interest is that of reducing the noise of aircraft. A few years ago NACA considered the problem

of reducing the noise reaching the ground from light airplanes in order to remove an objection to the construction of small airports in or near residential areas. Since then the increasing speed and power of transport aircraft and the development of still higher-powered jet airplanes have focused attention on the aircraft noise problem more generally. The principal sources of airplane noise are the engine exhaust and the propeller, and little improvement can be made unless both sources are attacked.

To reduce exhaust noise requires the development of suitable mufflers. Limitations on weight, size, and tolerable engine power loss are much more stringent for airplane mufflers than for the automobile mufflers customarily designed by cut-and-try methods. The problem was attacked by Davis, Stevens, and Moore of the NACA Langley Laboratory, on the basis of the modern acoustics theory of the physicists, using the filter theories of Stewart and Mason. For mufflers of a size suitable for light airplanes the filter elements may be treated as lumped impedances while wave propagation theory is applied to the main duct connecting the elements. For larger mufflers the wave theory must be used for the filter elements as well. Excessive sound pressures reduce the attenuation below the value computed by linear theory, and for the larger mufflers which would be required for engines of transport aircraft, the wave propagation is governed by a non-linear differential equation. While successful mufflers appear feasible for small low-powered aircraft, a satisfactory solution for the higher-powered engines has not yet been obtained. A report on this work is in preparation.

The sound spectrum and spatial distribution of propeller noise may be determined theoretically for the case of a rotating propeller on an aircraft at rest. (NACA Technical Memorandum 1195). The propeller is represented by a ring of acoustic doublets whose strength is directly proportional to the torque and thrust of the propeller. This theory and confirmatory measurements (NACA Technical Note 1354) have established a basis for the study of the possible reduction of propeller noise. The major factor is the tip speed of the propeller and the only known method of large reduction of propeller noise is to reduce the tip speed. Fig. 20 shows the variation of propeller noise with tip Mach number for propellers of two and six blades. Supersonic propellers, though extremely noisy, give less noise than would be estimated by extrapolation of the data at lower tip speeds. In any practical case reduction of tip speed requires increasing the number of blades, decreasing the propeller diameter as much as possible, and decreasing rotational speed. Gearing to the engine may be required with considerable weight penalty and possibly decreased performance of the aircraft in takeoff and climb. Reasonable compromises have been demonstrated (NACA Technical Note 2079) for small light airplanes, but it does not as yet seem feasible or safe to apply the same measures to large high-powered aircraft. Much more research and development is required.

The basic physical data on the spectrum and directional characteristics of propellers and jets are available. Thus Fig. 21 shows a typical spectrum of the noise from a propeller, showing the periodic character of

of the noise and the concentration of the energy at the harmonic frequencies of the fundamental. By contrast the typical spectrum of the noise from a jet engine in Fig. 22 shows the completely random character of the noise and the absence of spectral lines. Fig. 23 shows the directional patterns. For the propeller the noise is maximum in the plane of the propeller; for the jet the maximum is at a moderate angle to the axis of the jet.

From such data the noise levels to be expected under various circumstances can be predicted for points both inside and outside the airplane. With present knowledge the engineer can only inform the general public that all high-powered sources of energy make a great deal of noise, and that the known effective measures for reducing or isolating the noise in the neighborhood of such a source are much too heavy to be used on aircraft. The only certain method of reduction is more distance between the source and the observer. Both aeronautical engineer and citizen look hopefully to the physicist for new physical principles which might be applied to this problem. Engineers and scientists of the aeronautical industry and government aeronautical agencies are devoting much effort to noise reduction, but the laws of acoustics restrict the possibilities regardless of the effort.

The NACA has been successful, with aid of physicists Bolt and Beranek of the Acoustics Laboratory of the Massachusetts Institute of Technology, in solving a very severe noise problem in the ground testing of large ramjet engines in a large supersonic wind tunnel. Helmholtz resonators in the frequency range of 4 to 10 cycles per second were

designed and tested in a model of one-twelfth the proposed full scale. Noise attenuations predicted from the small scale experiments were realized in the final muffler. Fig. 24 shows a general view of the exit cone of the wind tunnel and its muffler. A diagram with some of the technical characteristics is shown in Fig. 25, while Fig. 26 shows a photograph at the intersection of the exit cone and the remainder of the muffler. A glance at the large and massive construction shows clearly the large gap between this highly successful muffler and a device suitable to be carried in an airplane.

CONCLUSION

This view of aeronautical research and development through glasses which transmit only problems in physics reveals a fertile field with no lack of opportunity for physicists to make large contributions. A complete survey would require a book rather than a single paper; hence only a few examples have been given of the application of existing physical knowledge, of problems in physics arising from the resolution of engineering problems into their component physical sub-problems, and of the great indebtedness of aeronautics to physics for its tools of measurement. For security reasons and to fulfill better the aim of this paper, emphasis has been placed on the longer range problems. This has given a very distorted view of the present content of aeronautical research and development and of the activities of the National Advisory Committee for Aeronautics in particular. Nevertheless, if only a few of the physicists who read this paper are stimulated to work in

areas of importance to aeronautics, a substantial contribution will have been made to the quality of future aircraft and hence to our national security.

End

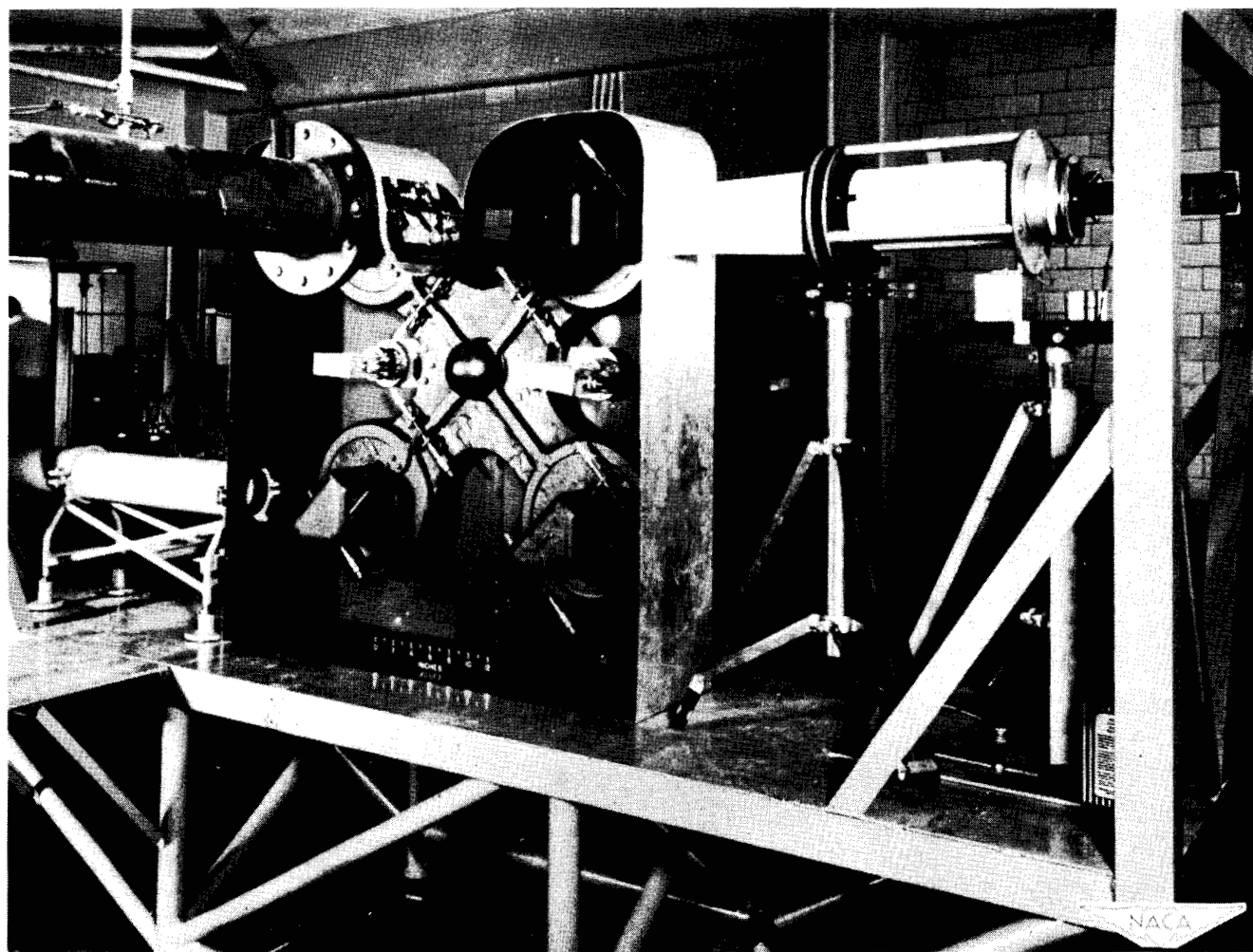


Fig. 1. Interferometer for Air Flow Studies.
Light source at left, camera at right, nozzle removed from
top center.

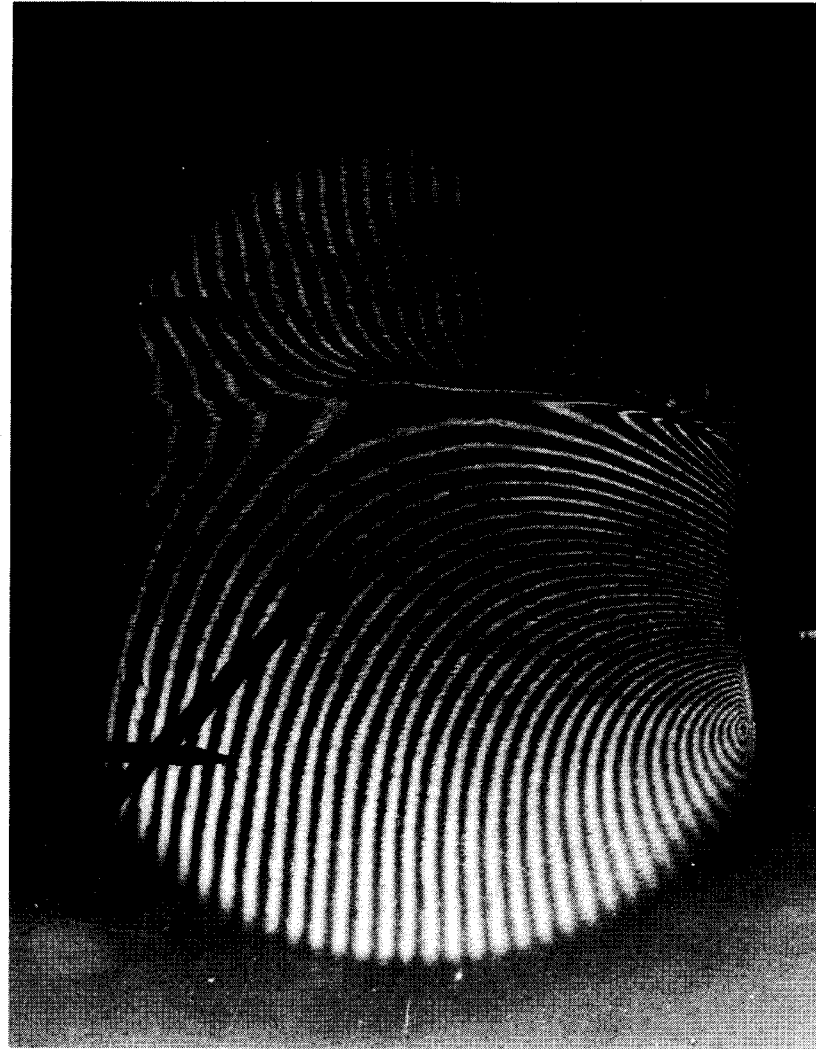


Fig. 2. Interferogram for Flow around Circular-Arc Airfoil.
Airfoil thickness 12 percent, Mach number 0.9, boundary
layer turbulent.



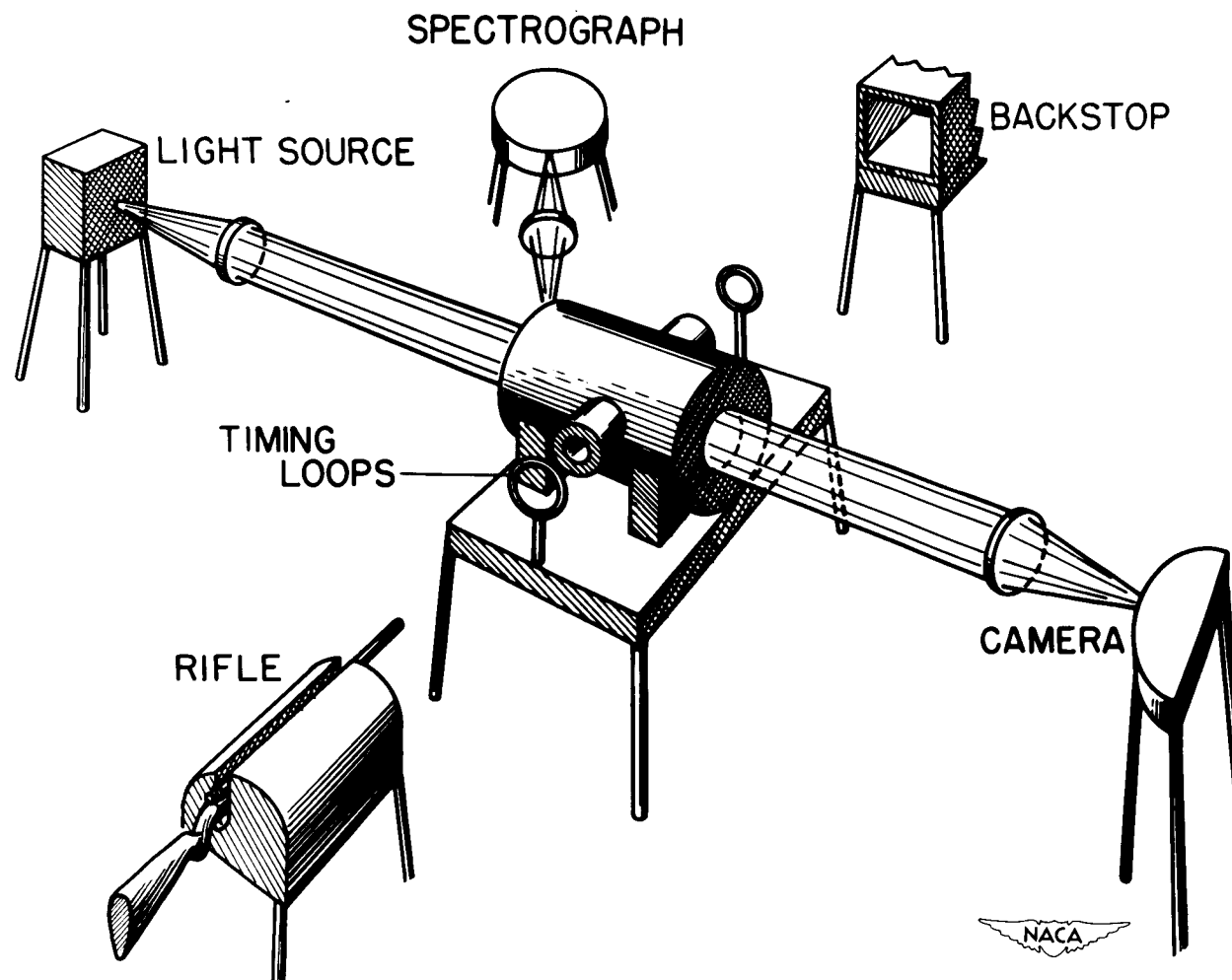


Fig. 3. Equipment for Study of Air Flow at Mach Numbers of 10 or More.
Chamber may contain any desired gas and may be cooled.

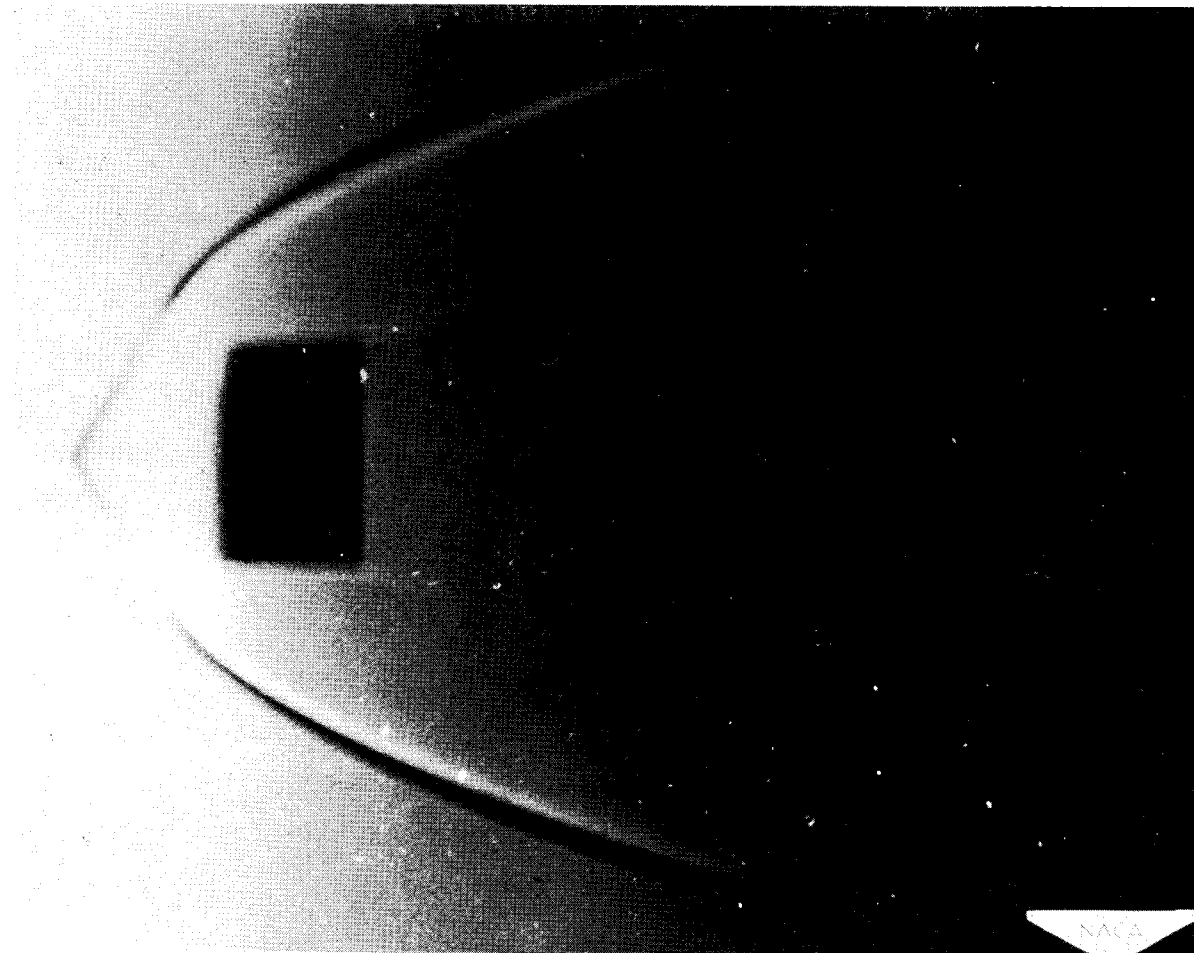


Fig. 4. Luminosity and Shock Wave Formation at Mach Number 11.
Projectile is 1/8-inch conical nose projectile of 90° apex
angle fired in Xenon gas at 74° F. and atmospheric
pressure.

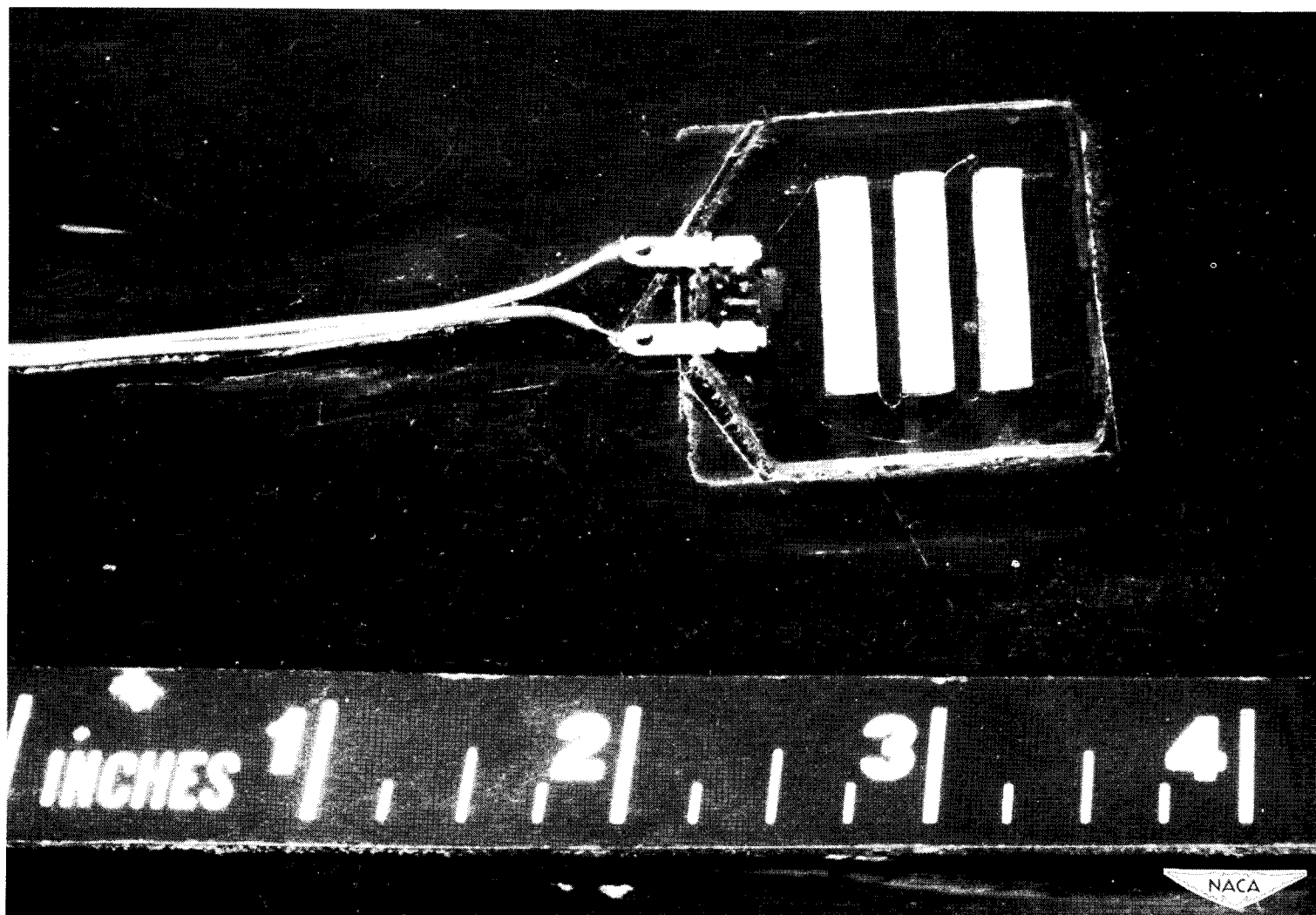


Fig. 5. Heat Flow Meter for Study of Aerodynamic Heating.

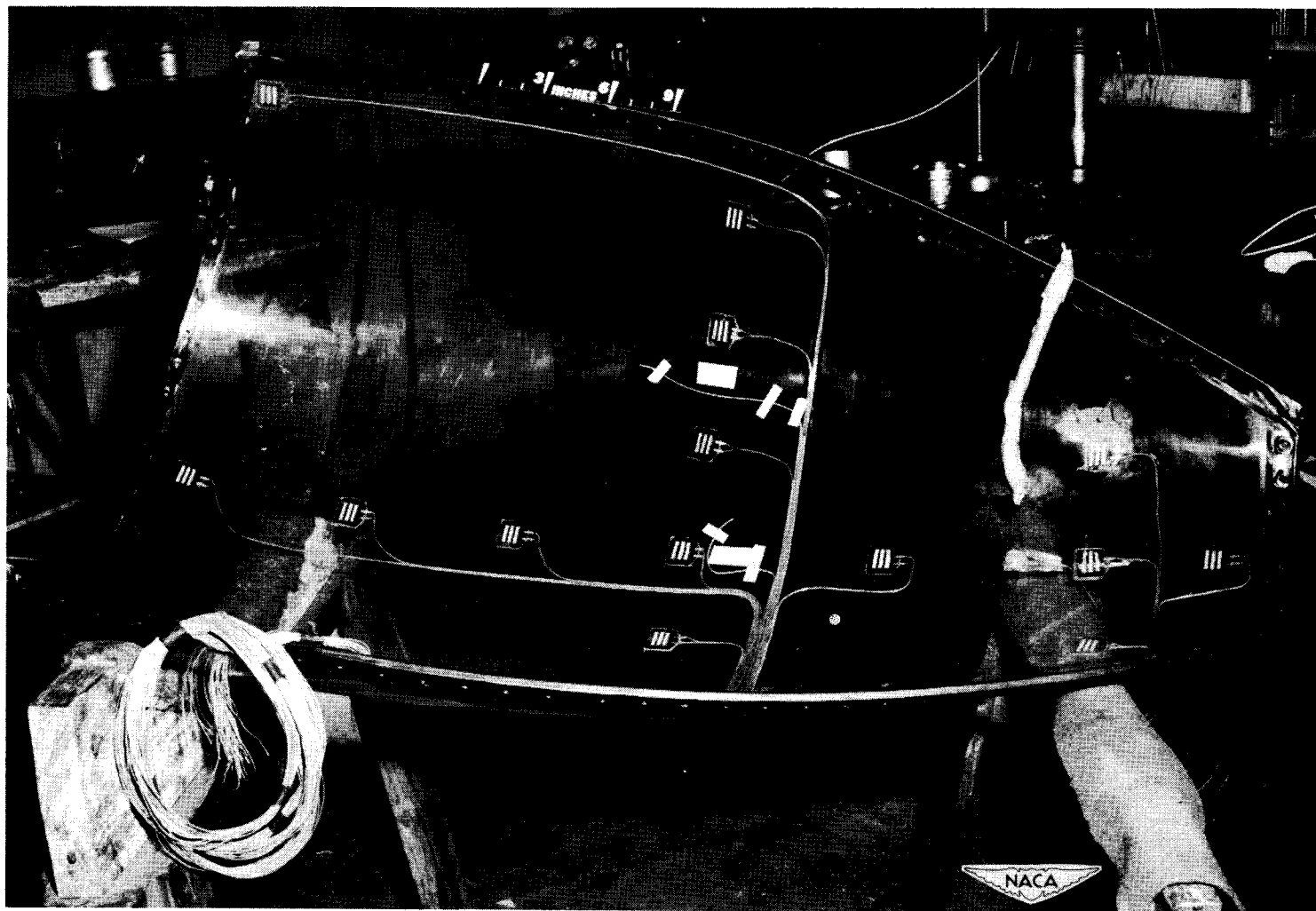


Fig. 6. Heat Flow Meters Mounted on Canopy of F-80 Airplane for Flight Tests.

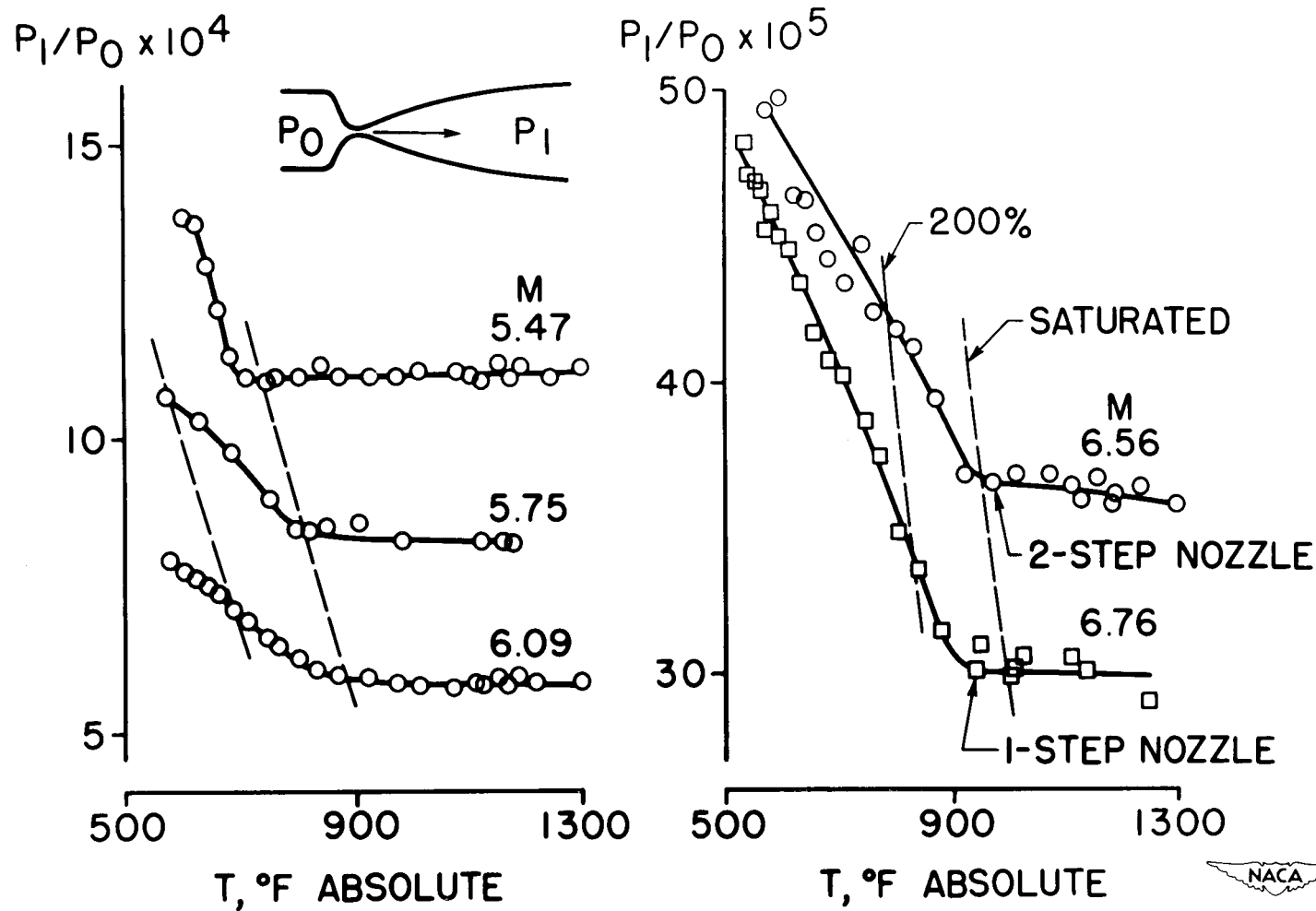


Fig. 7. Variation of Pressure as Function of Inlet Air Temperature Indicating Effect of Condensation.

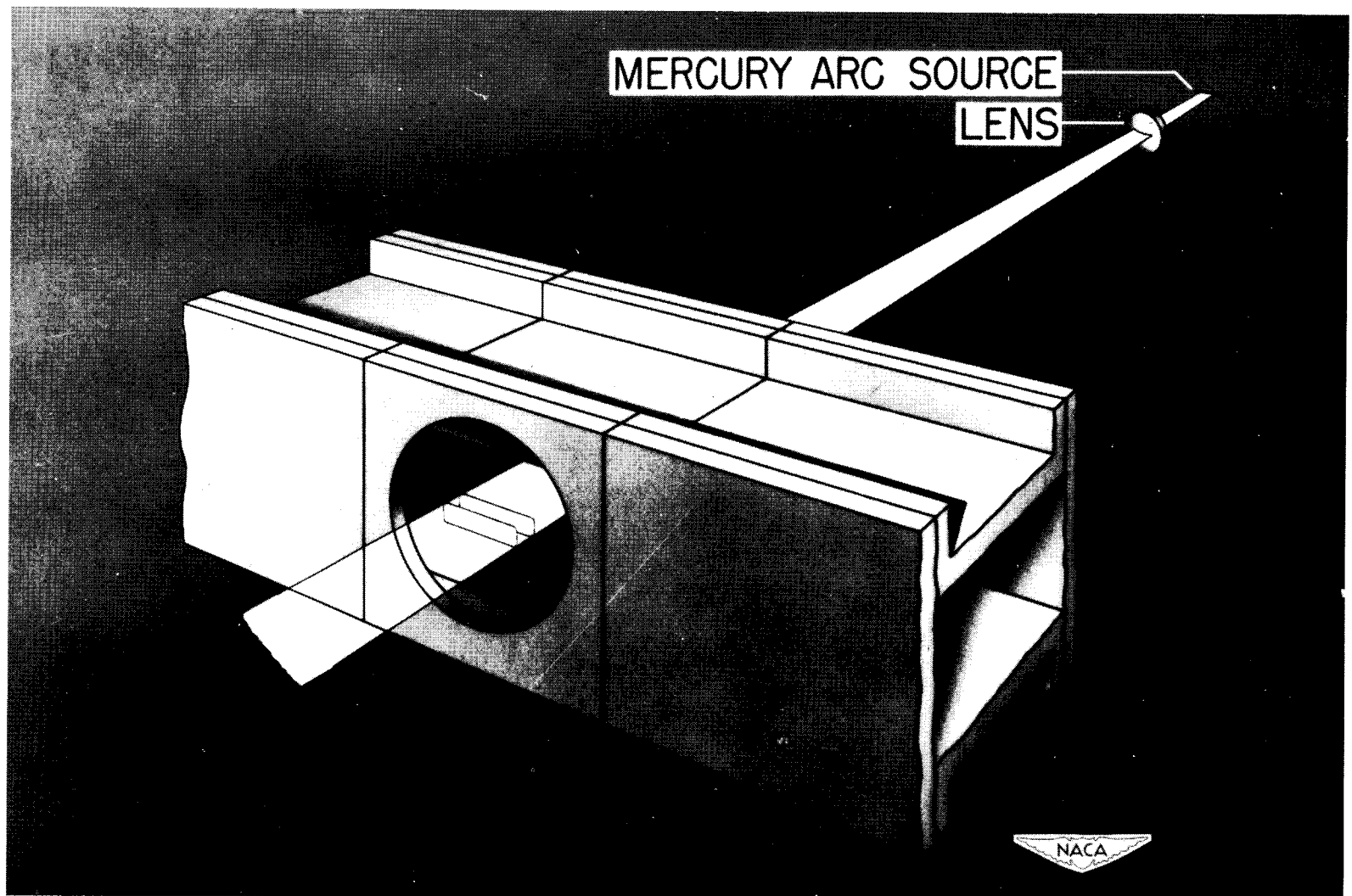
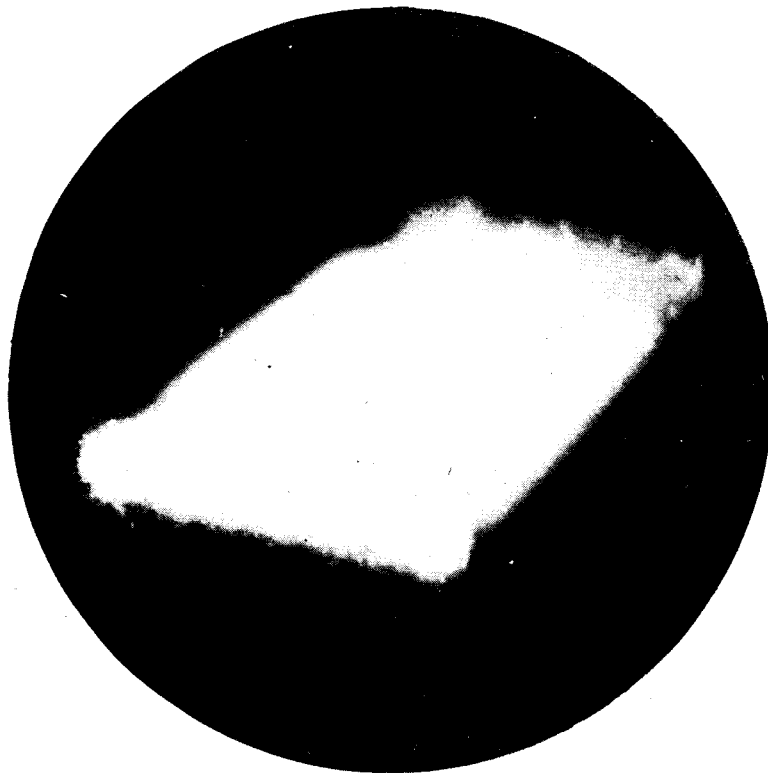


Fig. 8. Simple Light Scattering Apparatus for Detection of Condensation.



$T_0 = 540 \text{ } ^\circ\text{F abs.}$



$T_0 = 1160 \text{ } ^\circ\text{F abs.}$



Fig. 9. Appearance of Light Beam with and without Condensation.
Condensation appears at lower inlet air temperature at left.

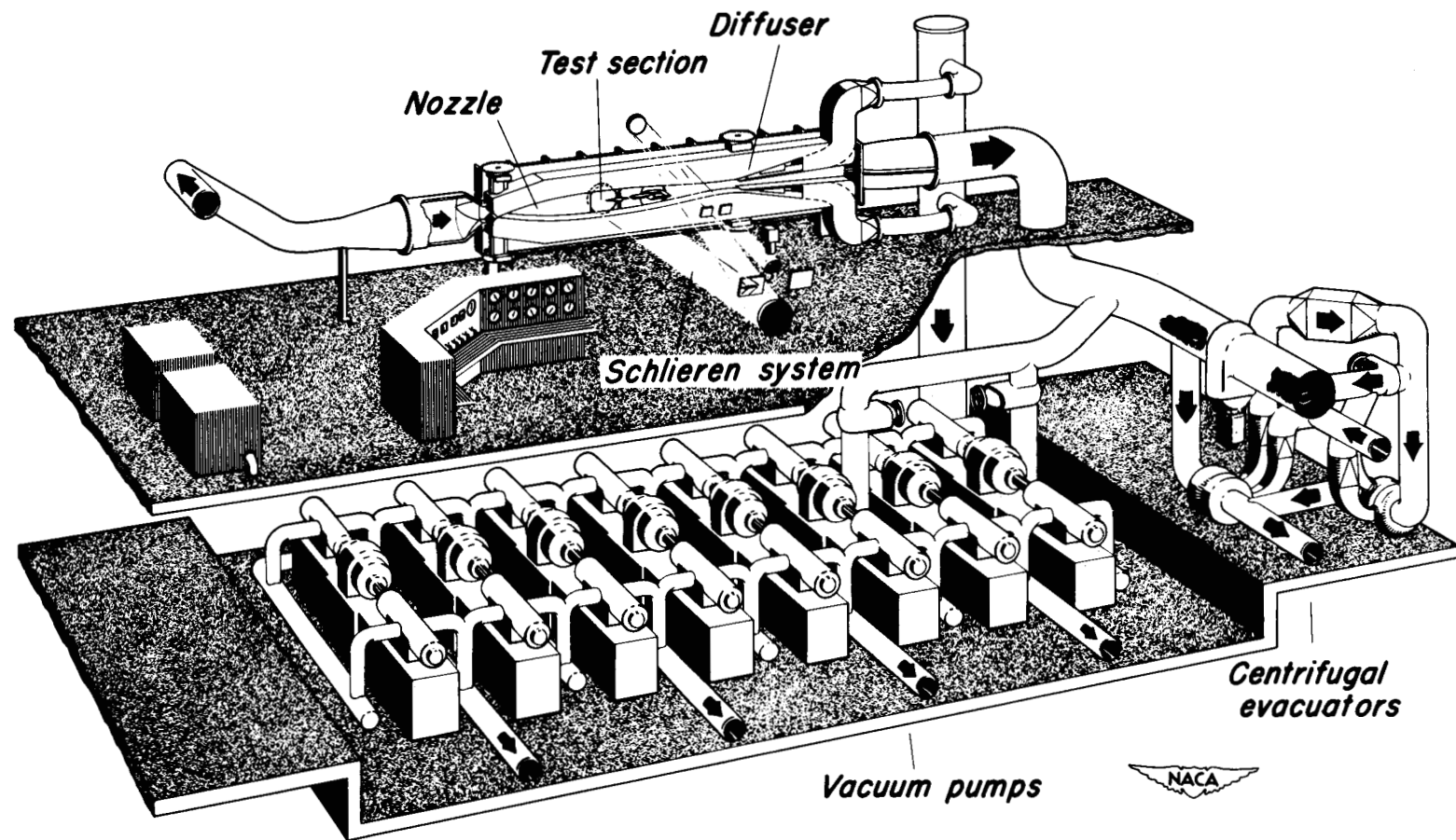


Fig. 10. The NACA Ames 10- by 14-Inch Hypersonic Wind Tunnel.

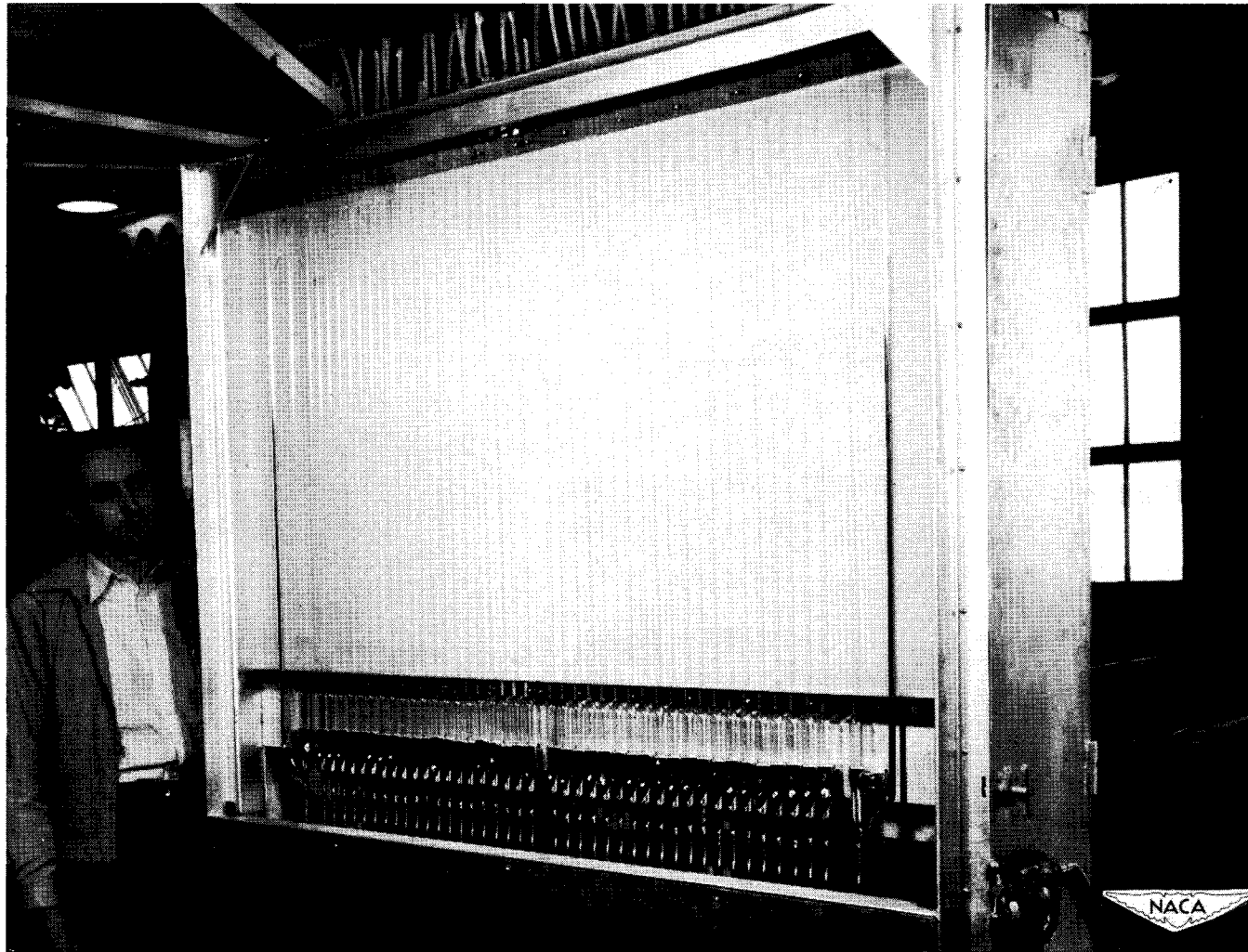
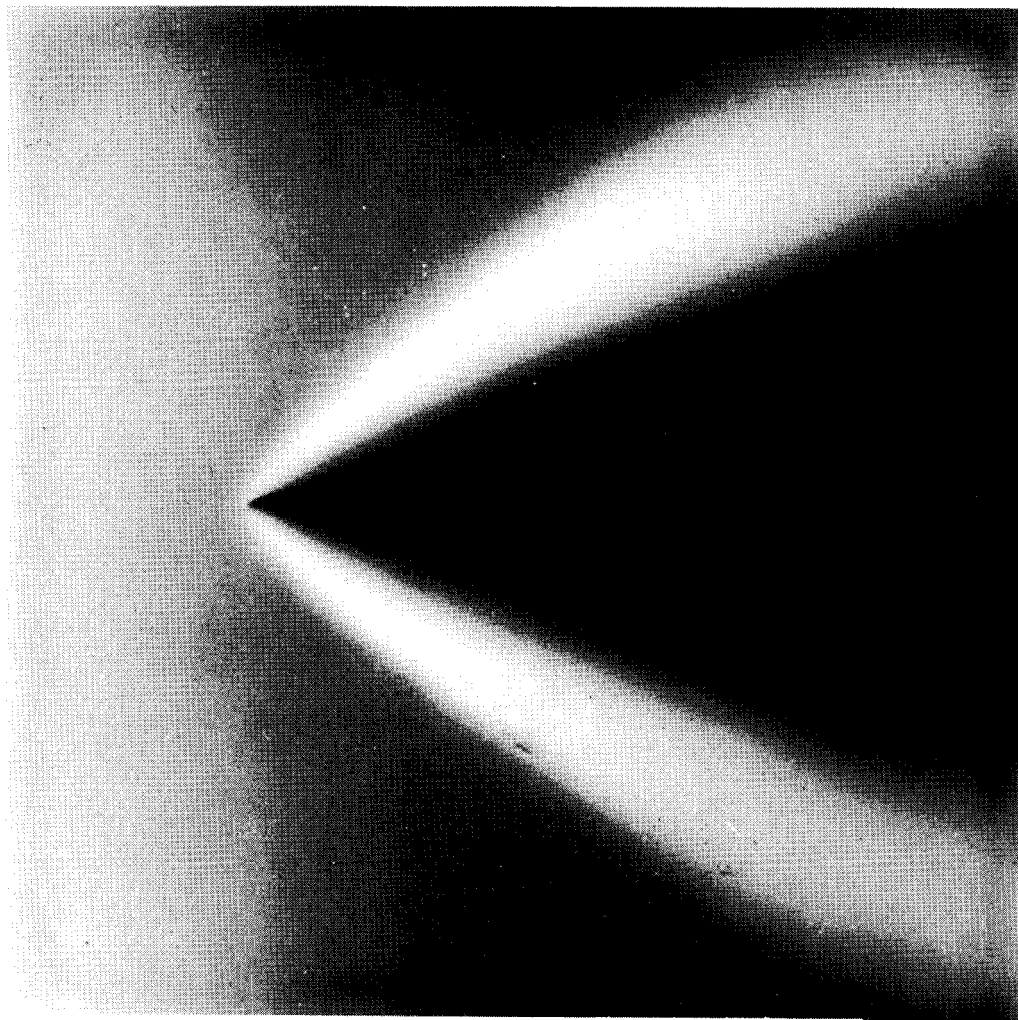


Fig. 11. Battery of Forty McLeod Gages with Common Sump for Pressure Measurements at Hypersonic Speeds.



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**Fig. 12. Photograph of Flow about 30° Wedge by Active Nitrogen Technique.
Stagnation pressure 140 microns of mercury, Mach number 2.**

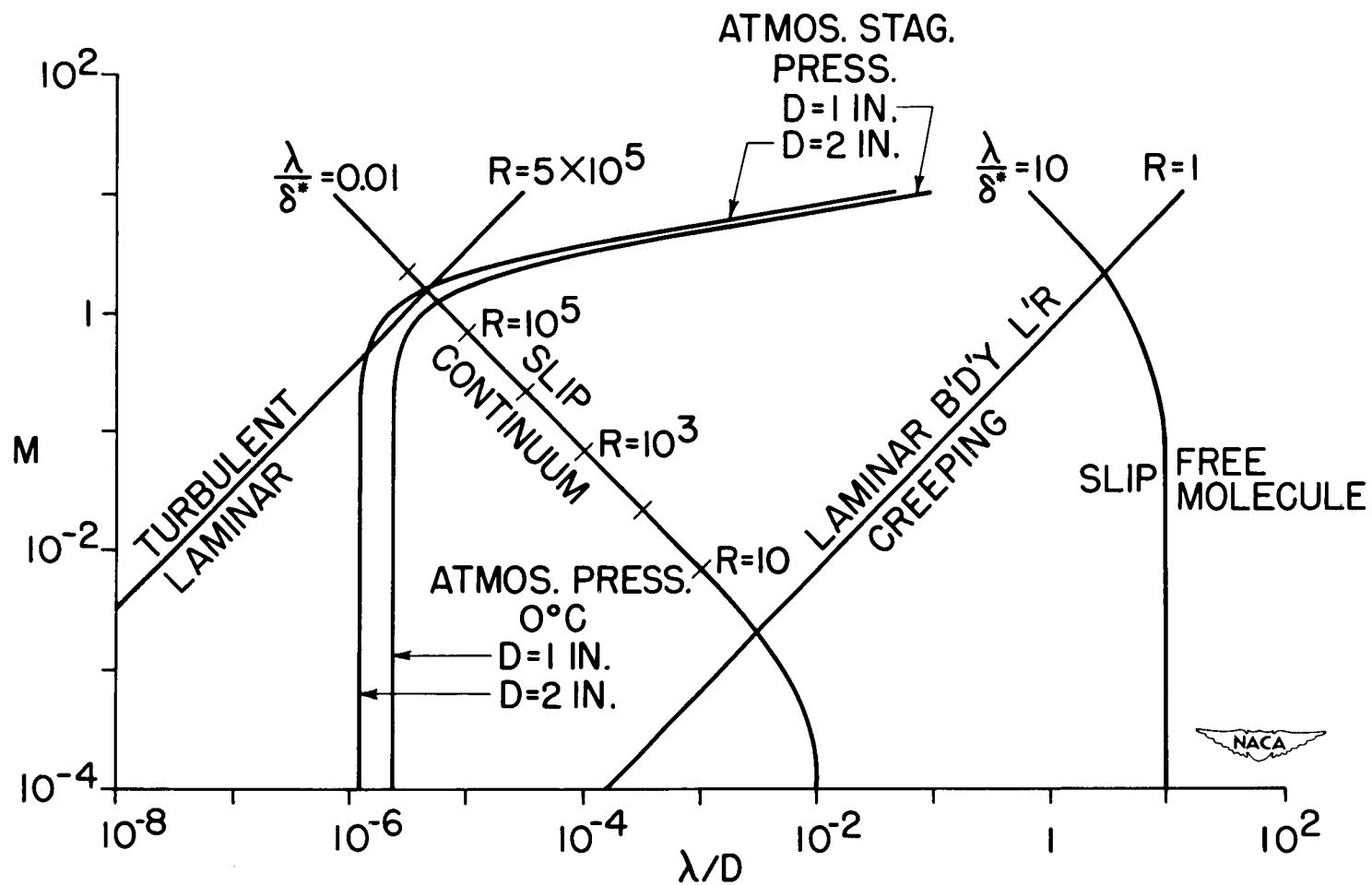
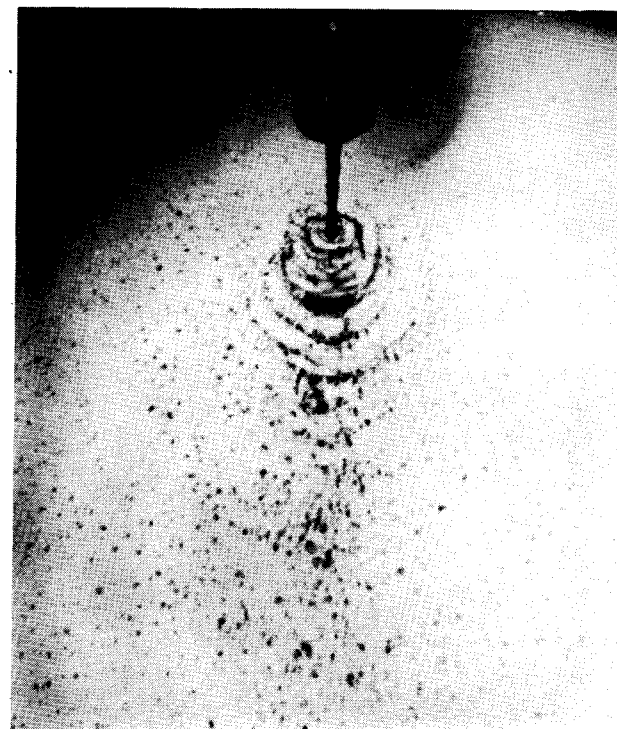


Fig. 13. Boundaries between Various Aerodynamic Regimes.
See text for explanation.



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Fig. 14. Spray Formation of Two Impinging Jets of Water.
Left, view at right angles to plane of jets; right, view in
plane of jets.

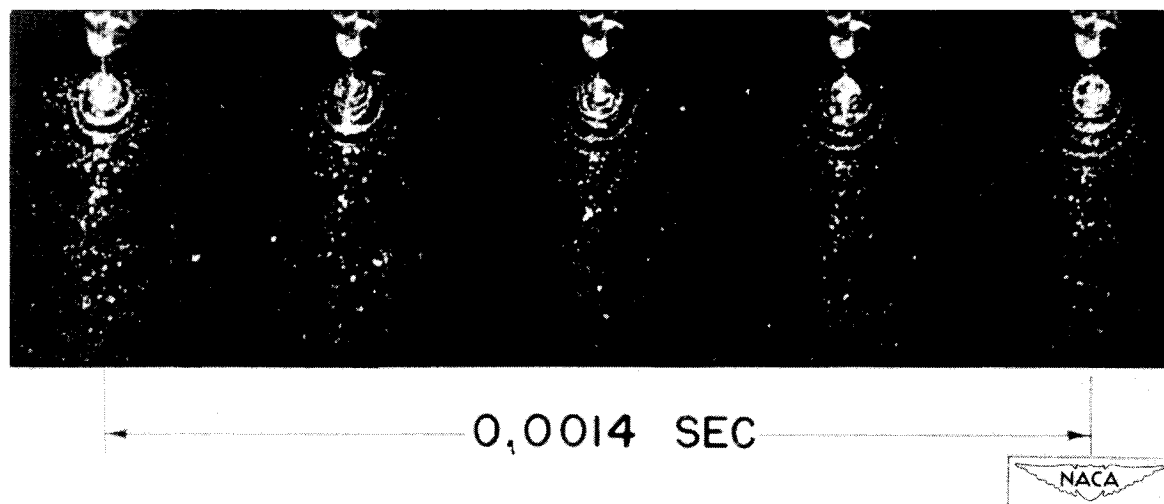


Fig. 15. High Speed Motion Pictures of Spray Formation of Impinging Jets.

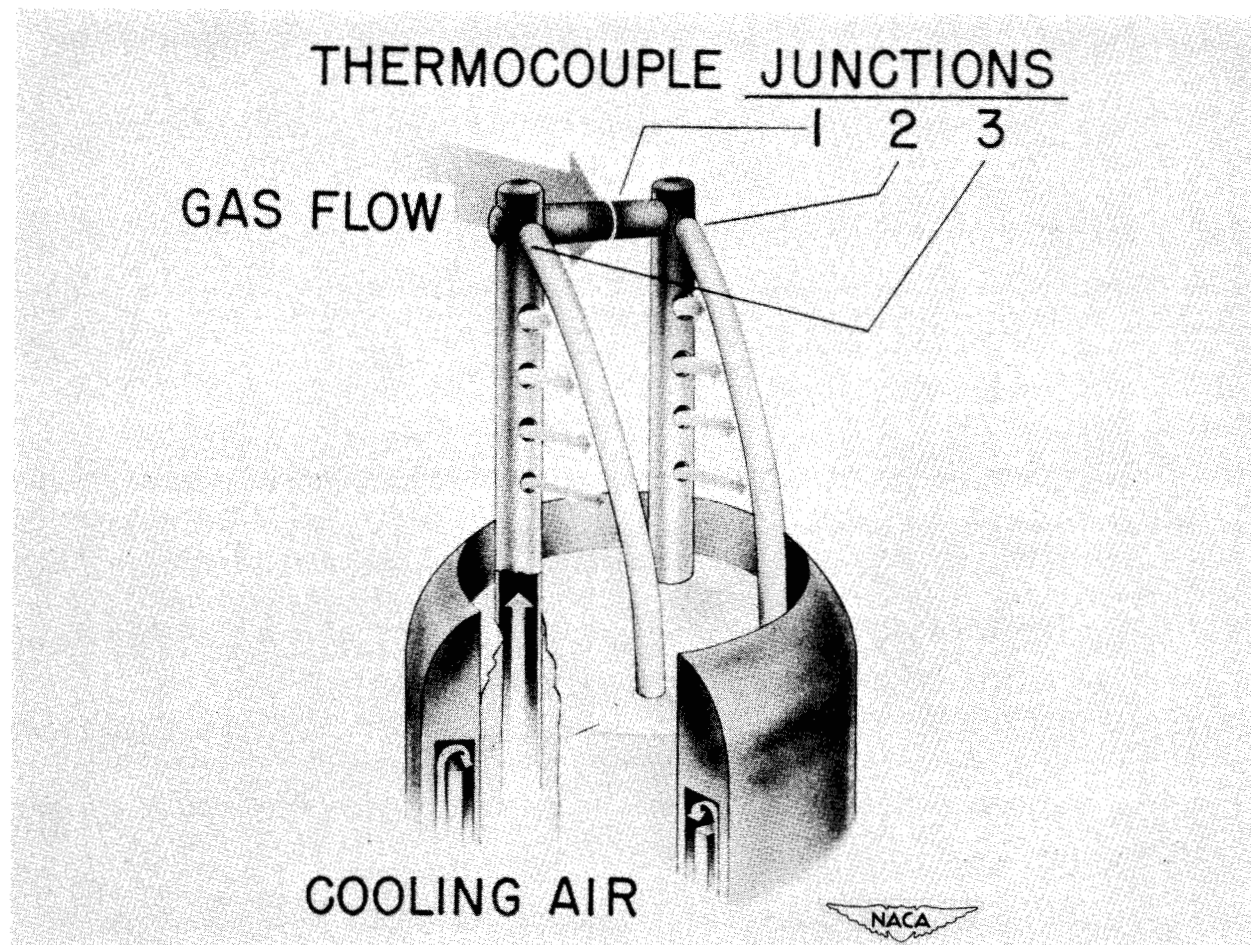
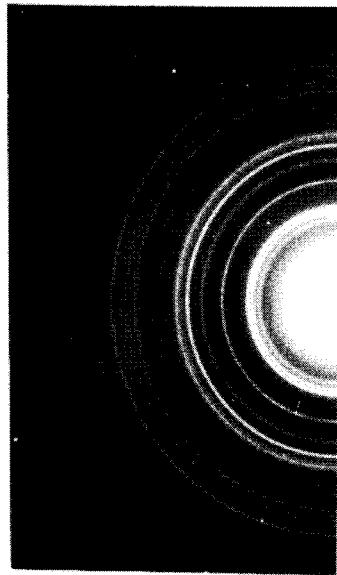
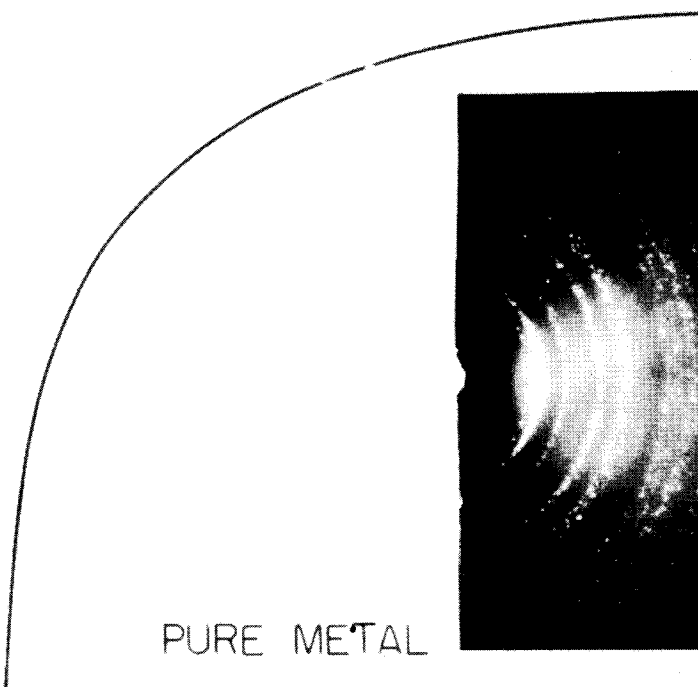


Fig. 16. Air-Cooled Thermocouple for Temperature Measurements of Gas Streams at Temperatures above the Melting-Point of Thermocouple.

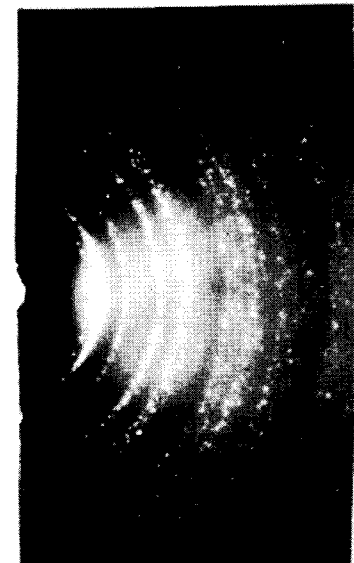
ELONGATION



OXIDIZED METAL



PURE METAL



TIME



Fig. 17. Influence of Surface Layer on Creep of Single Crystal of Zinc.
Oxide layer dissolved by acid at time corresponding to break
in elongation curve. Inset photographs are electron
diffraction patterns.

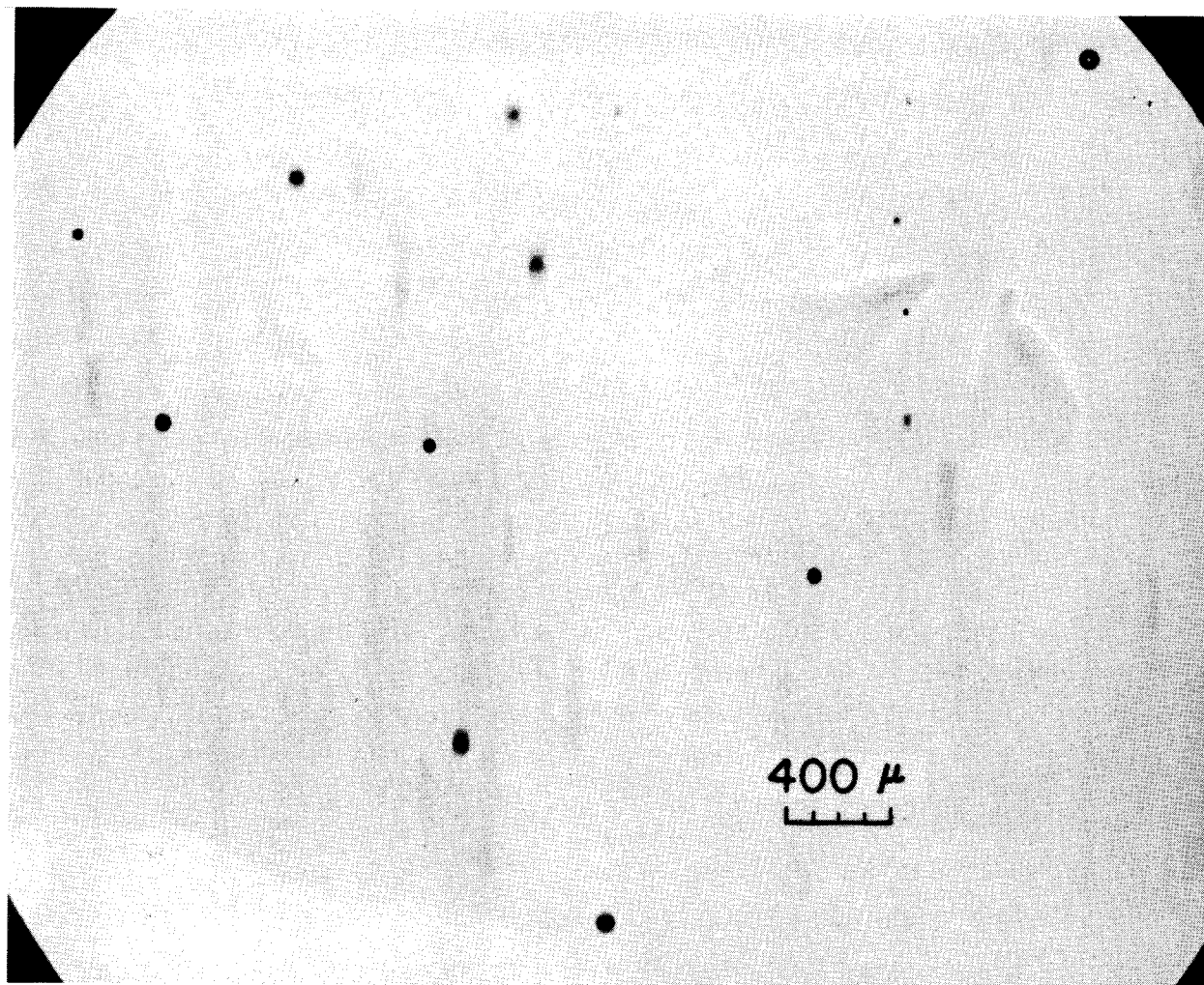


Fig. 18. Shadowgraphs of Cloud Droplets.



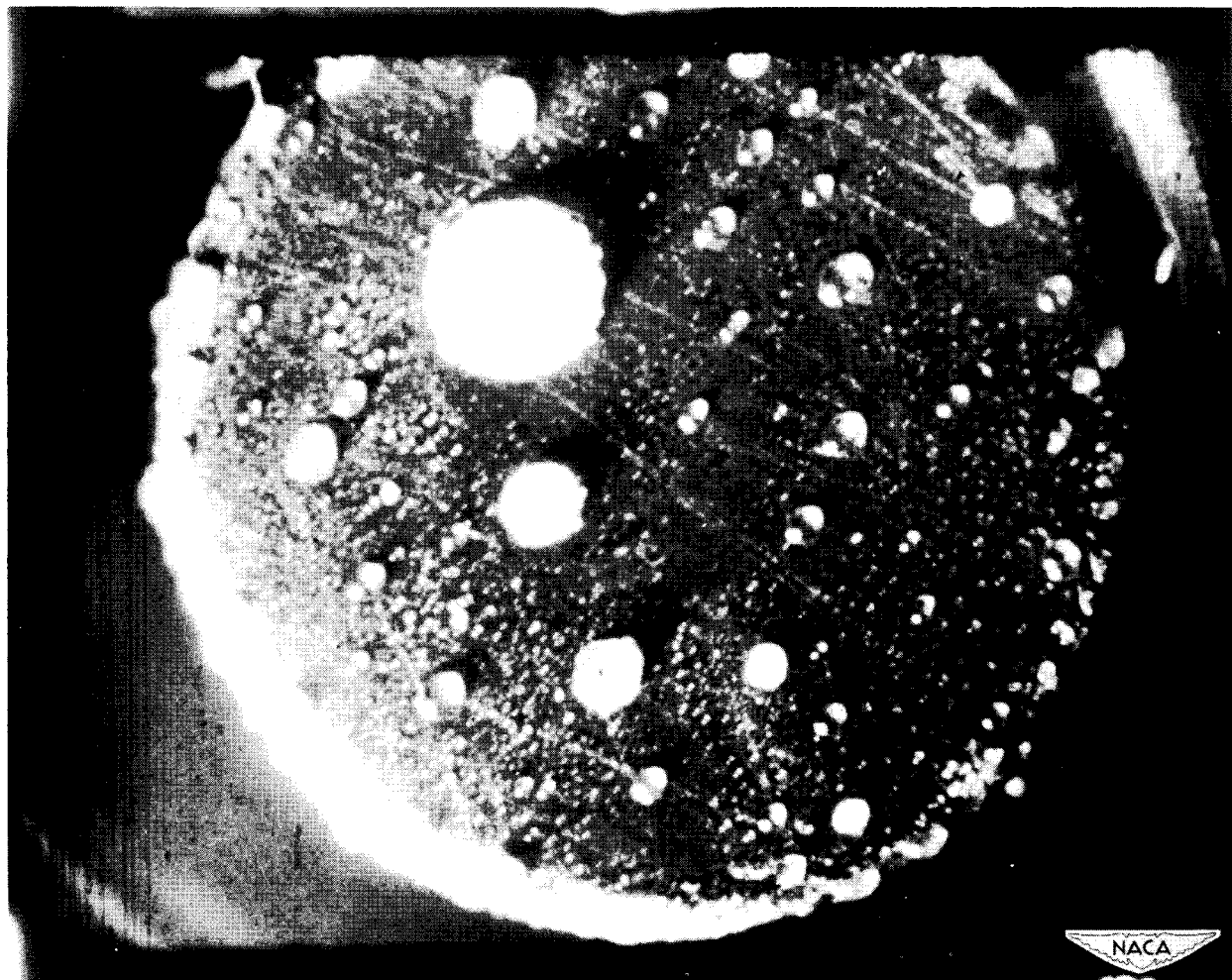


Fig. 19. Water Droplets Freezing on a Cooled Plate.
Temperature of plate -10° F. Largest droplet of 500 microns
diameter froze at 0° C. Liquid drops show highlights.

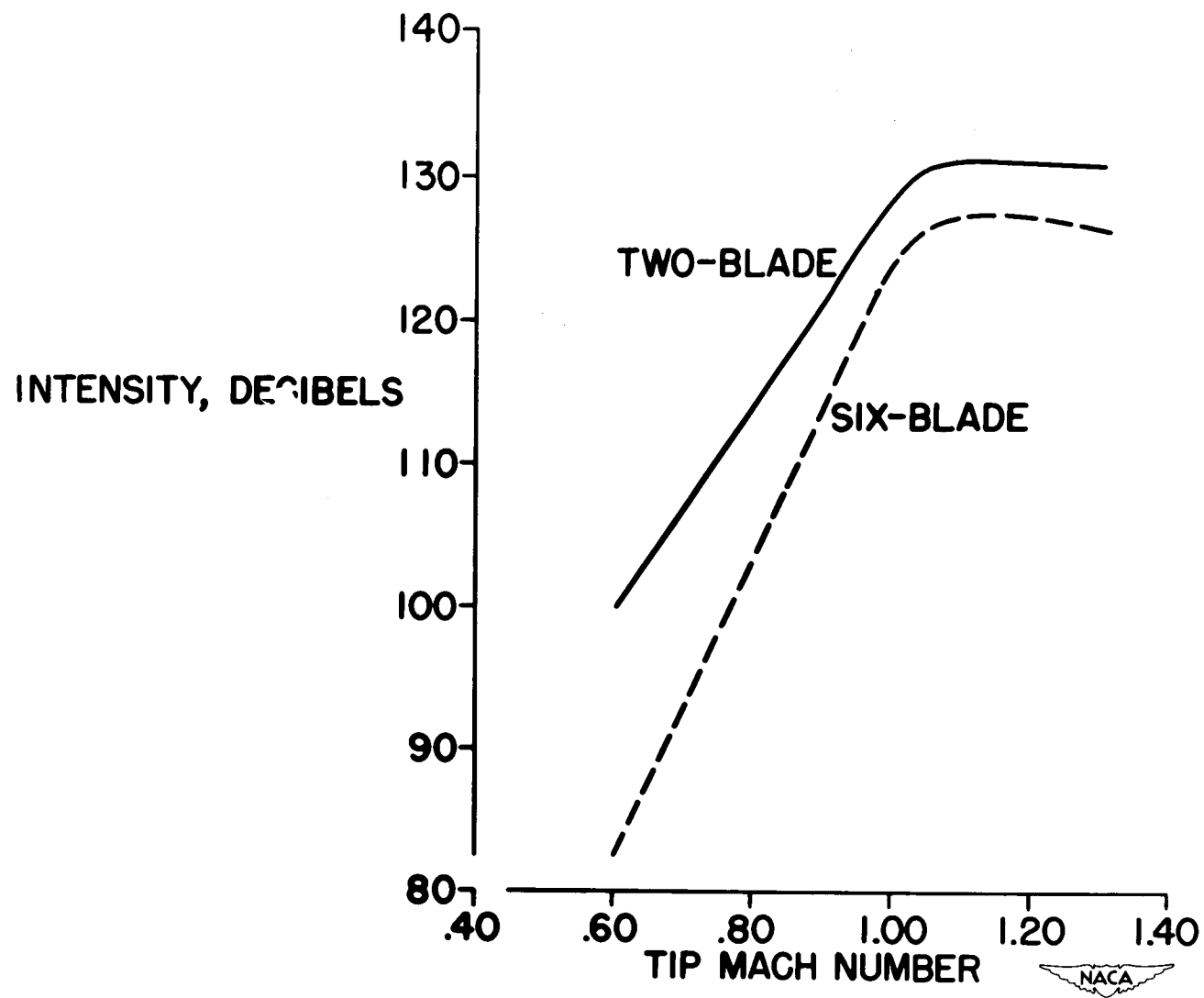


Fig. 20. Noise of Propellers as Function of Tip Mach Number.

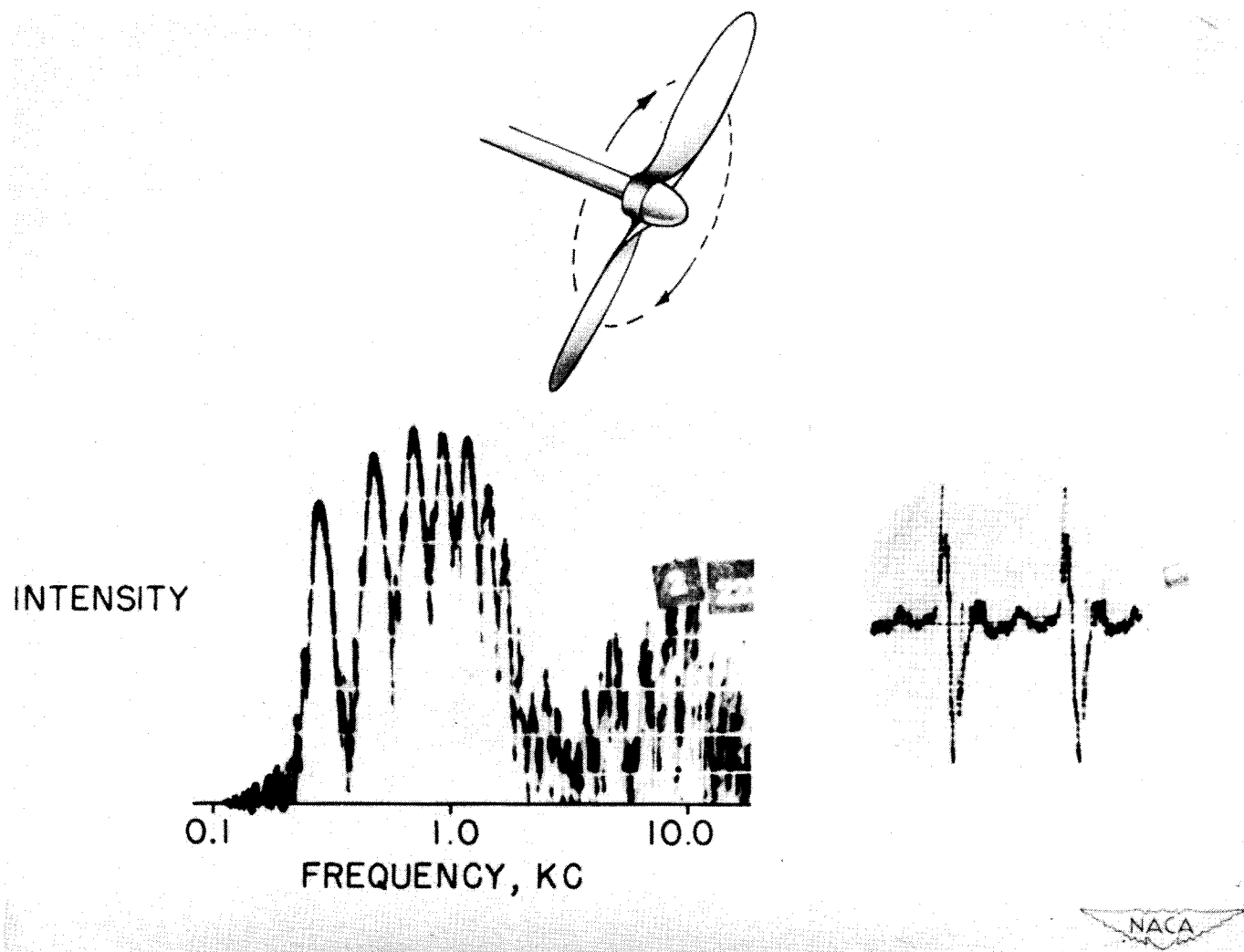


Fig. 21. Typical Spectrum and Oscillogram of Propeller Noise.

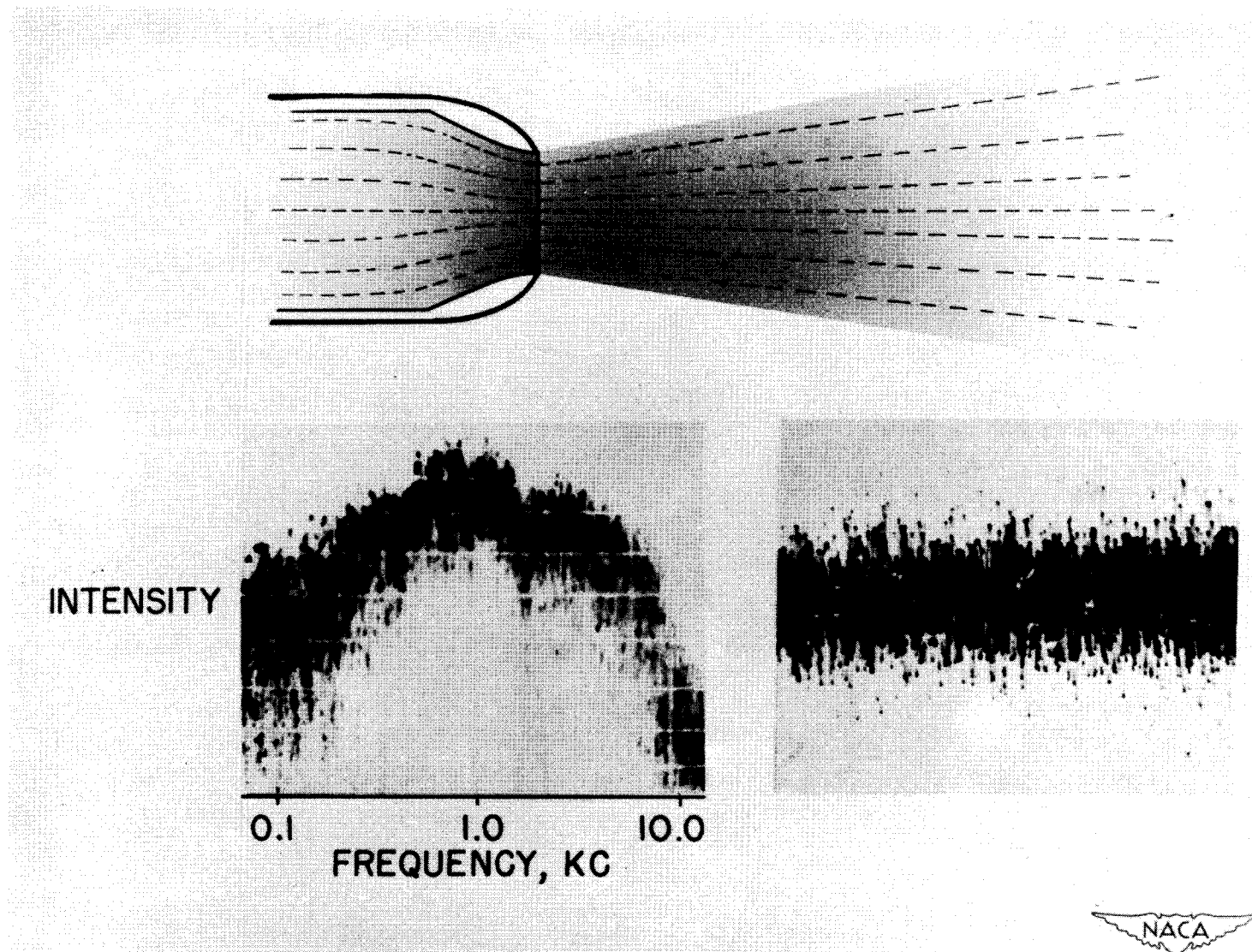


Fig. 22. Typical Spectrum and Oscillogram of Jet Noise.

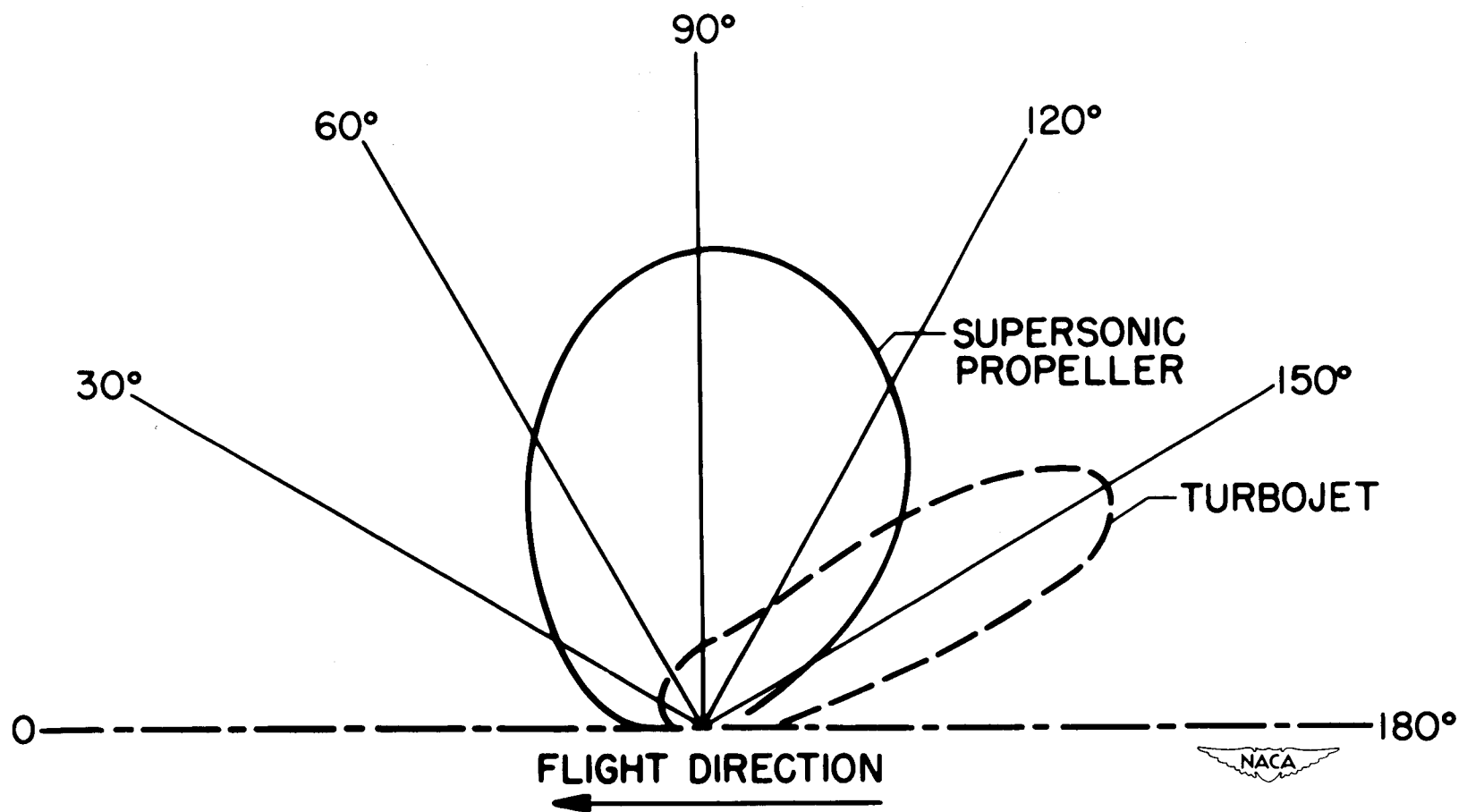


Fig. 23. Directional Characteristics of Propeller and Jet Noise.

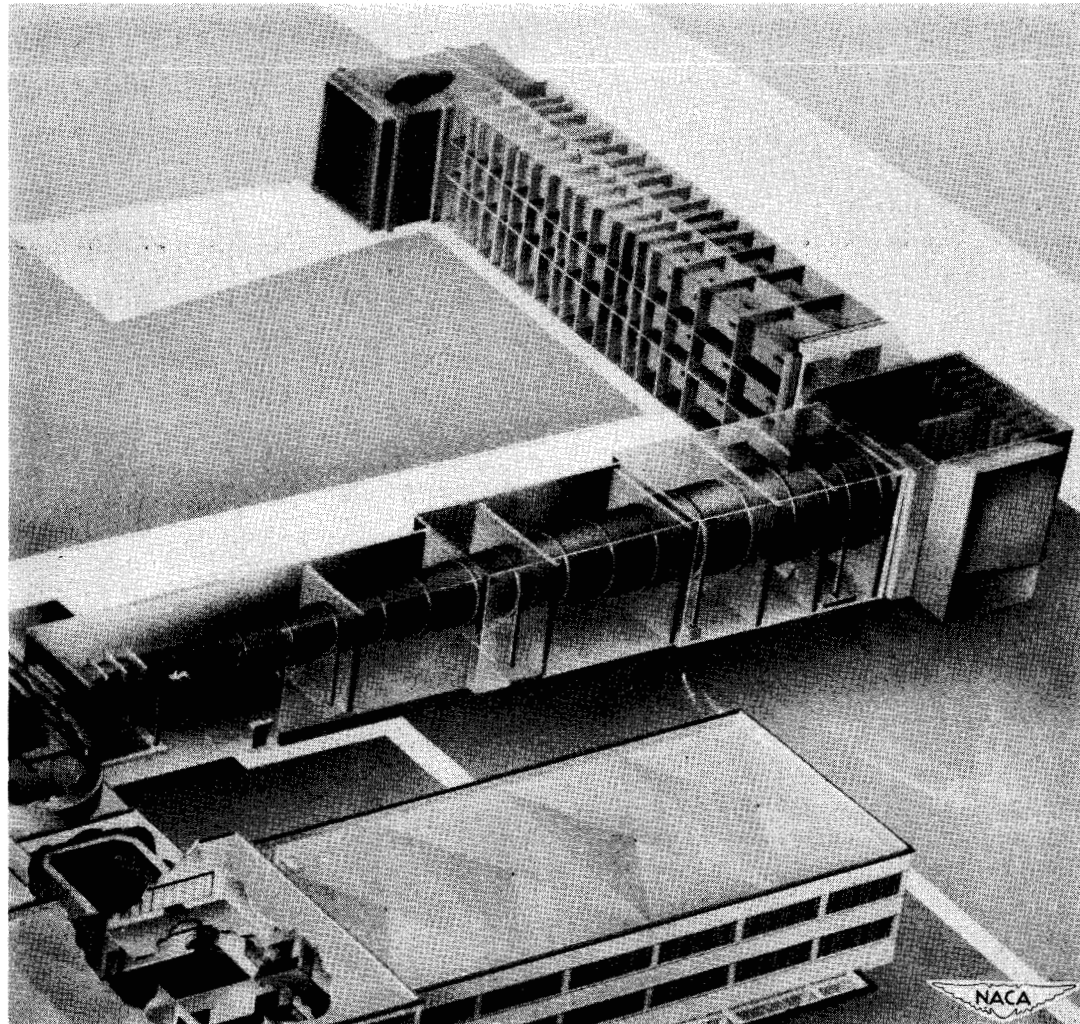


Fig. 24. Cutaway View of NACA Lewis Laboratory 8- by 6-Foot Supersonic Wind Tunnel and Muffler.

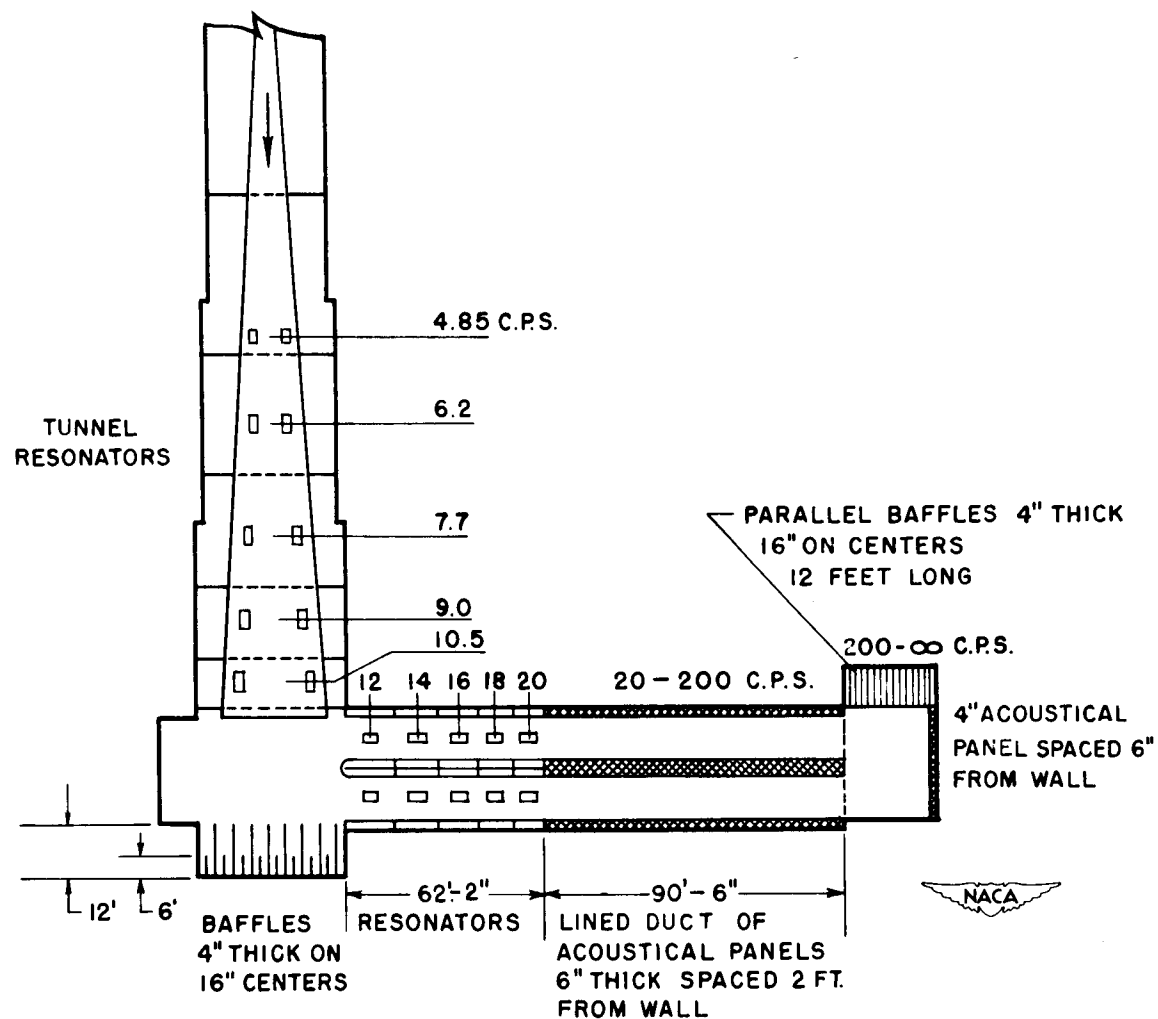


Fig. 25. Cross-Section of Wind Tunnel Muffler.



Fig. 26. Interior View of Wind Tunnel Muffler.